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Title:	Topic: Overview Fuel Cell Program Hydrogen Technologies/Value Chain
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Issued:	2020-11-16

Rod Borup (LANL)

Distributed Fuel Cell Program Manager

Topic: Overview Fuel Cell Program

Hydrogen Technologies/Value Chain

Los Alamos
NATIONAL LABORATORY
EST.1943

NNSA

FCHEA Roadmap

Fuel Cell and Hydrogen Energy Association (FCHEA)
http://www.fchea.org/us-hydrogen-study

Road Map to a US Hydrogen Economy

Executive Summary - Access Here

Full Report - Access Here

View our National and California launch webinars below.

New Report Offers Road Map to US Hydrogen Energy Leadership

US Hydrogen Study/Roadmap

Potential benefits of hydrogen in the US in the ambitious scenario – by the numbers

Hydrogen in the US could …

Strengthen the US economy, supporting up to:	Create a highly competitive source of domestically produced low-emission energy	Provide significant environmental benefits and improve air quality	Benefit the US energy system
~$140 bn in revenue 0.7 m jobs	~100% domestically produced	Less CO_2, NO_x, SO_x, and particulate emissions in cities	
… in 2030			
~$750 bn in revenue 3.4 m jobs	~100% domestically produced	-16% CO_2 -36% NO_x	~14% of final energy demand
… in 2050			

This report was developed with input from 19 companies and organizations:

- Air Liquide
- American Honda Motor Co., Inc
- Audi
- Chevron
- Cummins Inc.
- Daimler AG: Mercedes-Benz Fuel Cell GmbH/Mercedes-Benz Research & Development North America
- Engie
- Exelon Corporation
- Hyundai Motor Company
- Microsoft
- Nikola Motors
- Nel Hydrogen
- Plug Power
- Power Innovations
- Shell
- Southern California Gas Company
- Southern Company Services, Inc.
- Toyota
- Xcel Energy

H2@Scale: Technical & Economic Potential

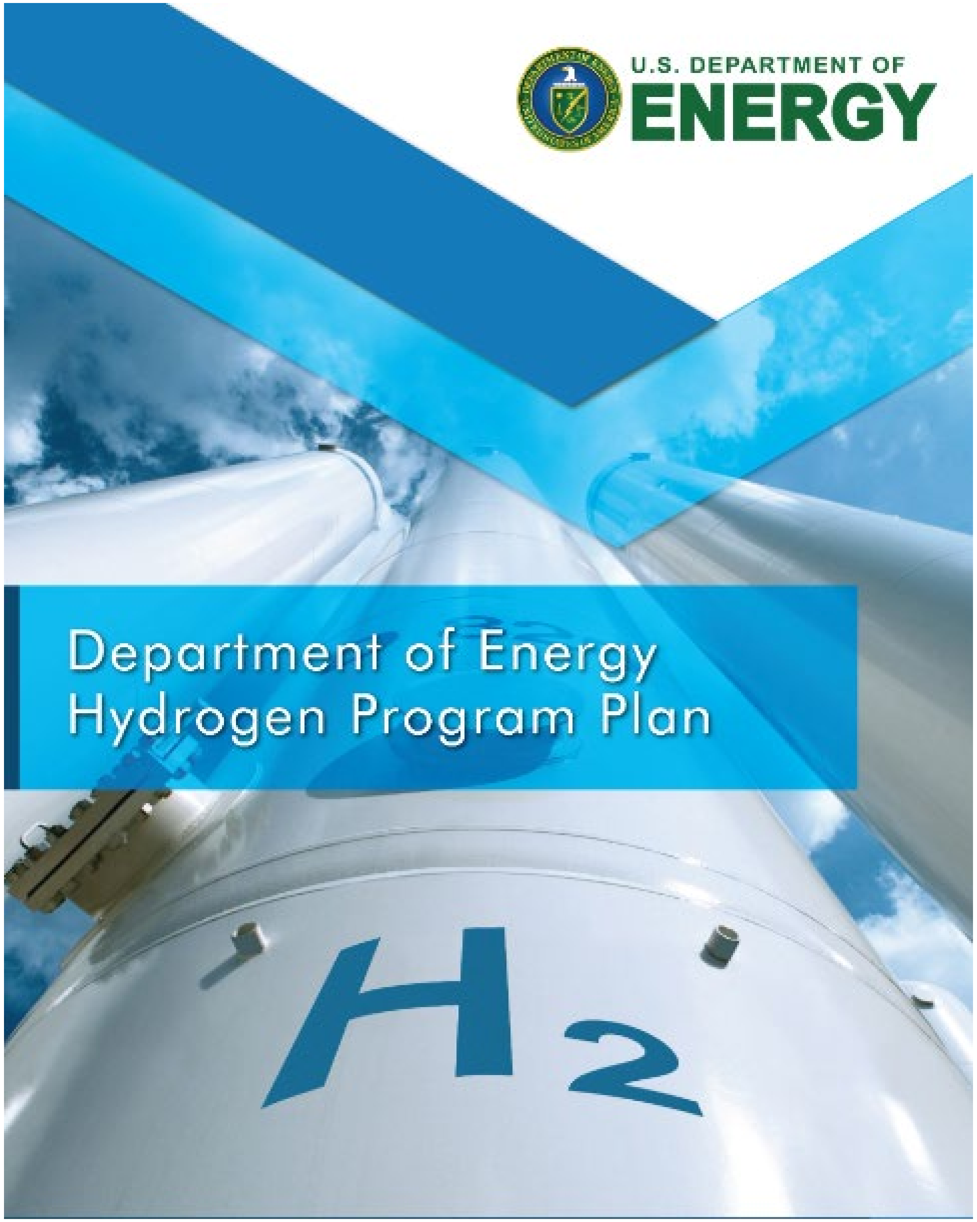
The Technical and Economic Potential of the H2@Scale Concept within the United States

Mark F. Ruth,[1] Paige Jadun,[1] Nicholas Gilroy,[1] Elizabeth Connelly,[1] Richard Boardman,[2] A.J. Simon,[3] Amgad Elgowainy,[4] and Jarett Zuboy[5]

1 National Renewable Energy Laboratory
2 Idaho National Laboratory
3 Lawrence Livermore National Laboratory
4 Argonne National Laboratory
5 Independent Contractor

196 page report
From Hydrogen & Fuel Cells Office
Released: October 2020

DOE EERE HFTO Hydrogen Program Plan



https://www.hydrogen.energy.gov/roadmaps_vision.html

HFTO Program Roadmap

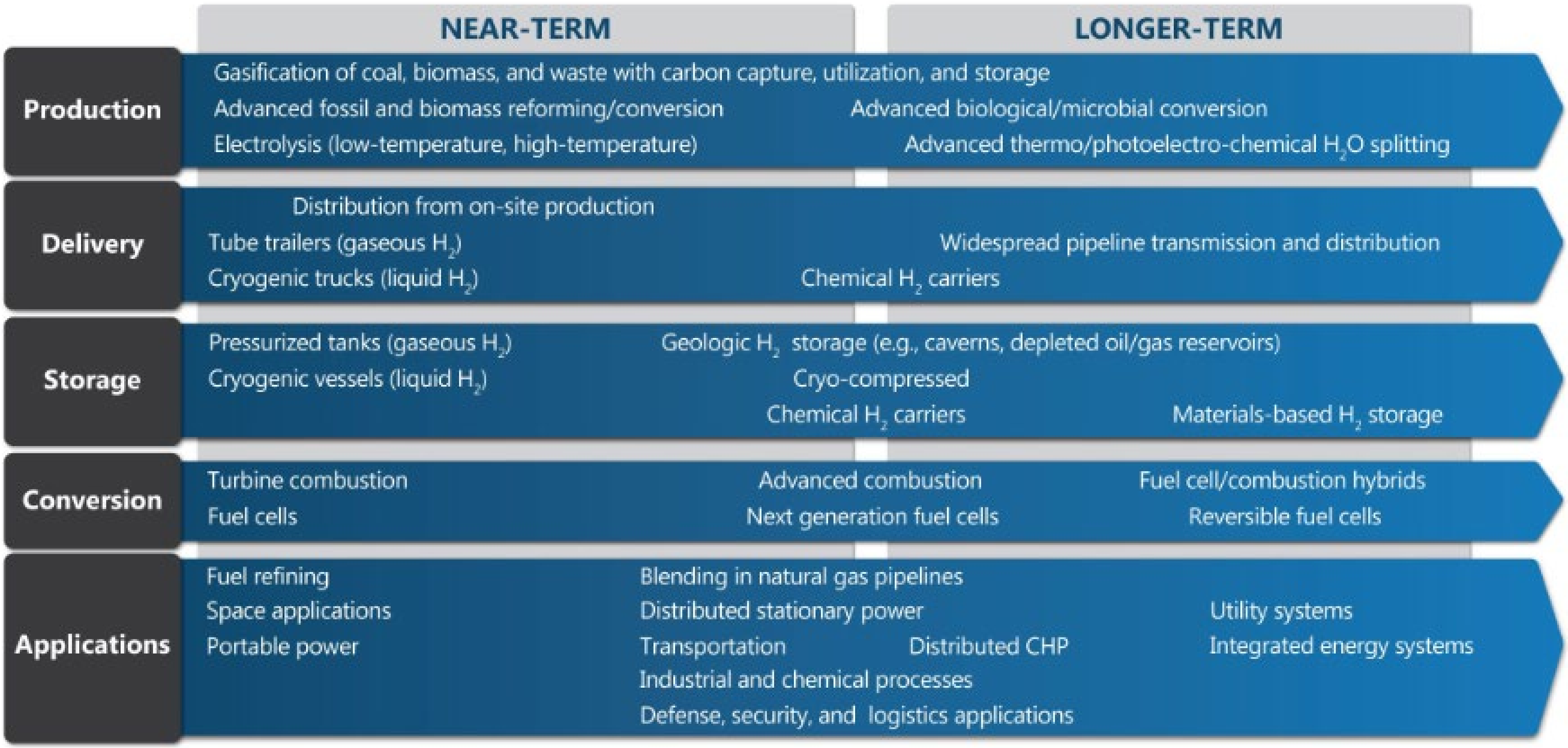
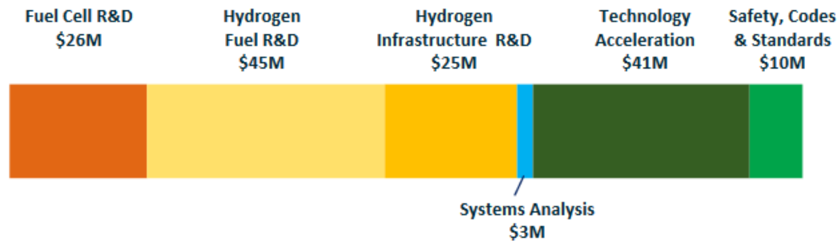


Figure 2. Key hydrogen technology options

Budget and Focus Areas in EERE H_2 and Fuel Cell Technologies Office

EERE HFTO Activities	FY 2020 ($K)
Fuel Cell R&D	**26,000**
Hydrogen Fuel R&D	**45,000**
Hydrogen Infrastructure R&D (included in Hydrogen Fuel in FY21)	25,000
Systems Development & Integration (Technology Acceleration)	**41,000**
Safety, Codes, and Standards (included in Systems Development & Integration in FY21)	10,000
Data, Modeling and Analysis	**3,000**
Total	**$150,000**

Hydrogen and Fuel Cells Breakdown FY 2020



- **Production:** Water splitting – electrolysis (high and low temperature), PEC, STCH, biomass/biological
- **Infrastructure:** Materials, delivery, components & systems
- **Storage**: materials-based, carriers, tanks, liquid
- **Fuel cells**: materials, components, systems, reversible FCs
- **Systems Development & Integration:** Tech Acceleration includes hybrid/grid integration, new markets, heavy duty, energy storage, manufacturing industrial applications (e.g. steel) safety, codes, standard, workforce development

**Will be moved under Hydrogen Fuel R&D in FY 2021*

Note: Office of Fossil Energy covers fossil fuels to H_2

FY21 Senate Mark for HFTO: $150M

- not less than $45,000,000 for technologies to advance hydrogen use for heavy-duty transportation and industrial applications.
- $45,000,000 for Hydrogen Fuel Research and Development for efforts to reduce the cost and improve the performance of hydrogen generation and storage systems, hydrogen measurement devices for fueling stations, hydrogen compressor components, and hydrogen station dispensing components.
- $25,000,000 is recommended for Hydrogen Infrastructure Research and Development with emphasis on large-scale hydrogen production including liquefaction plants, hydrogen storage, and development of hydrogen, including pipelines.

Snapshot of Hydrogen and Fuel Cells Applications in the U.S.

Examples of Applications

>500MW
Stationary Power

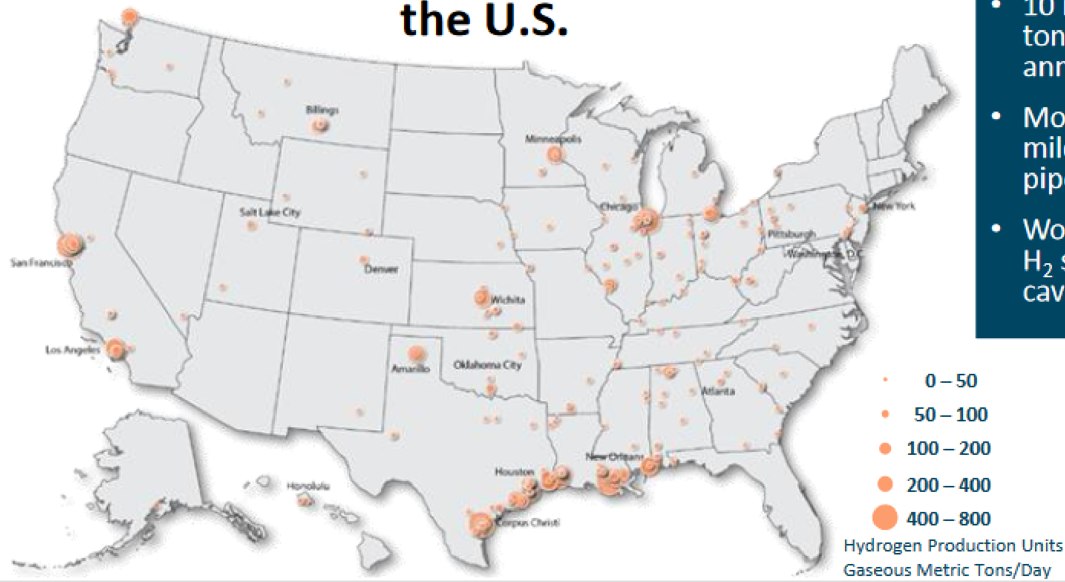
>35,000
Forklifts

>60
Fuel Cell Buses

>45
H_2 Retail Stations

>8,800
Fuel Cell Cars

Hydrogen Production Across the U.S.



- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Hydrogen Stations: Examples of Plans Across States

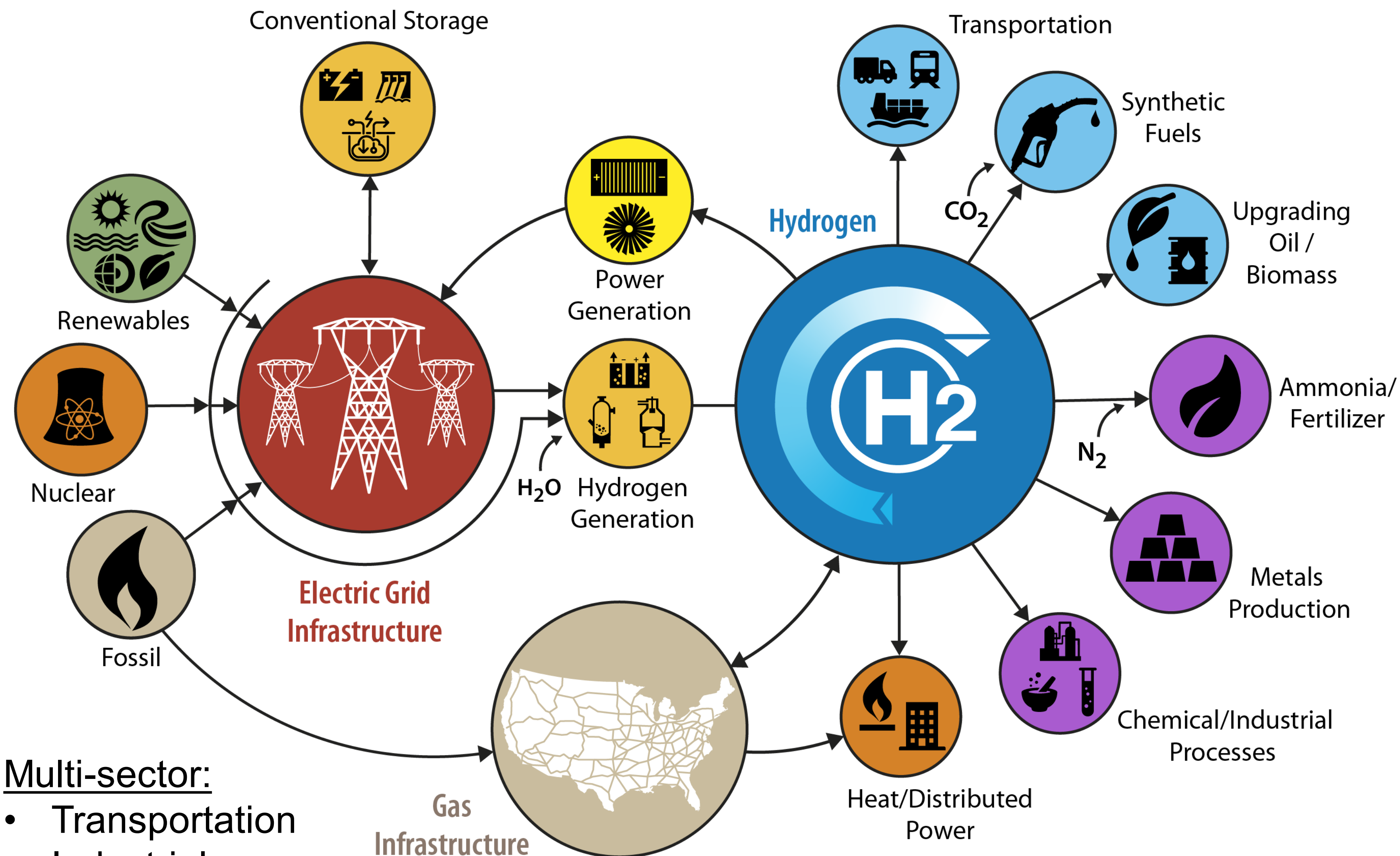
California
200 Stations Planned
CAFCP Goal

Northeast
12 – 20
Stations Planned

HI, OH, SC, NY, CT, MA, CO, UT, TX, MI
And Others

Dr. Sunita Satyapal, HOC (Hydrogen Online Conference), Mission Hydrogen-October 8, 2020

Conceptual H_2 at Scale Energy System*



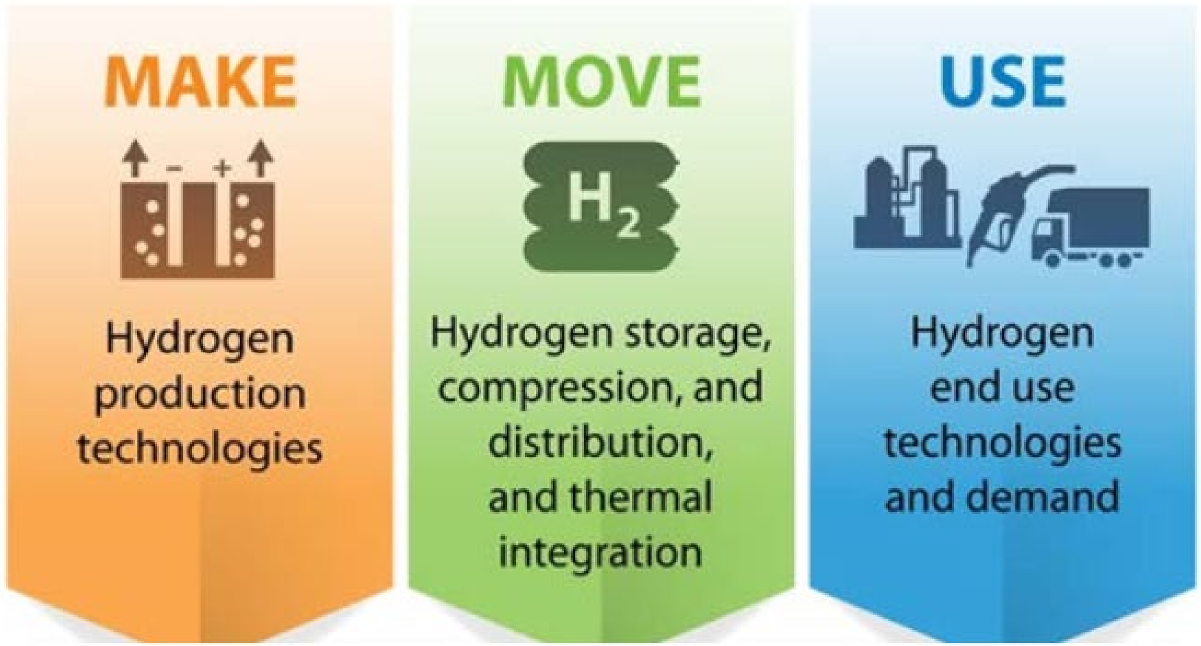
Multi-sector:

- Transportation
- Industrial
- Grid

*Illustrative example, not comprehensive

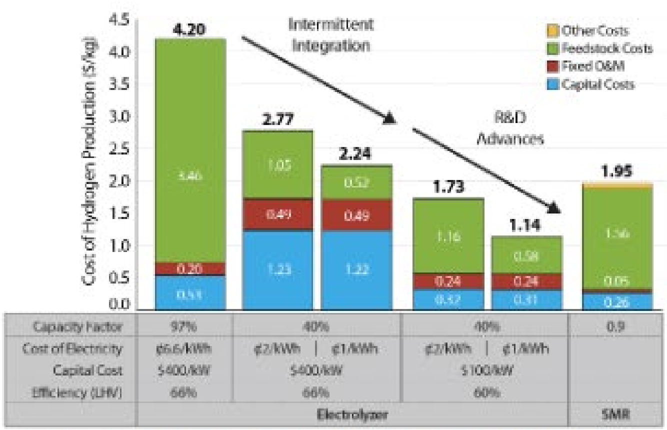
Improving the economics of H2@Scale

Early-stage research is required to evolve and de-risk the technologies

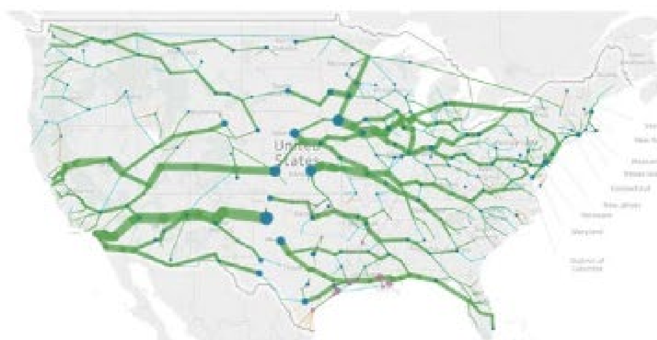


Preliminary

Use	Potential MMT/yr
Refineries & CPI	8
Metals	6
Ammonia	5
Methanol	1
Biofuels	1
Natural Gas	7
Light Duty Vehicles	28
Other Transport	3
Electricity Storage	28
Total	**87**



Decreasing cost of H_2 production



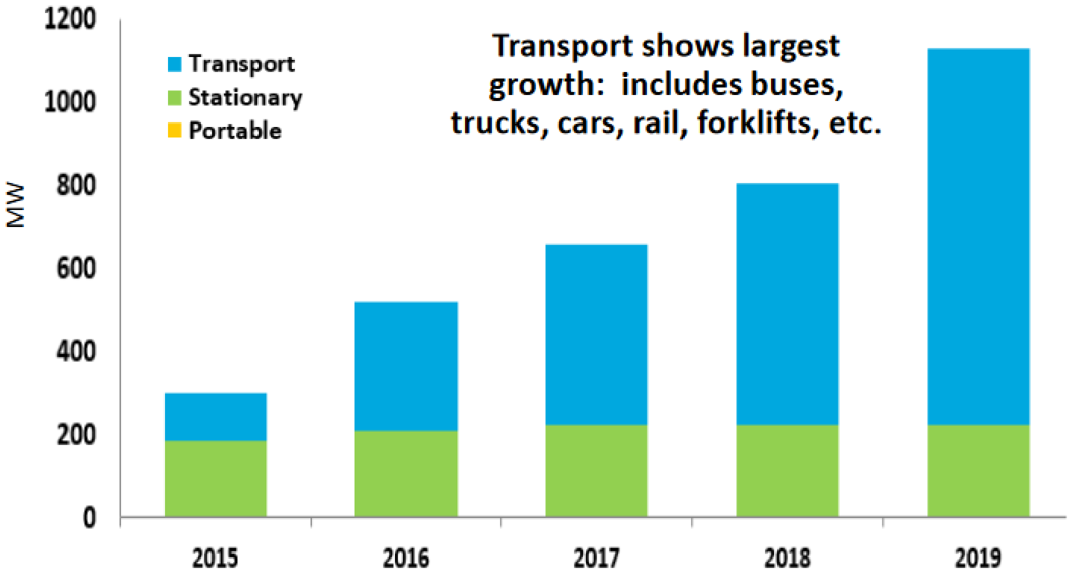
Optimizing H_2 storage and distribution

Leveraging of national laboratories' early-stage R&D capabilities needed to develop affordable technologies for production, delivery, and end use applications.

https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

Hydrogen and Fuel Cell Technology Growth Worldwide

Global fuel fell shipments surpass 1 GW



Source: E4tech for DOE analysis project

25-fold increase in electrolyzers deployed in the last decade

<1MW in 2010 to >25 MW by the end of 2019

Global FCEVs doubled to >25,200

>12.3K sold in 2019 vs. 5.8K in 2018

470 H_2 fueling stations worldwide

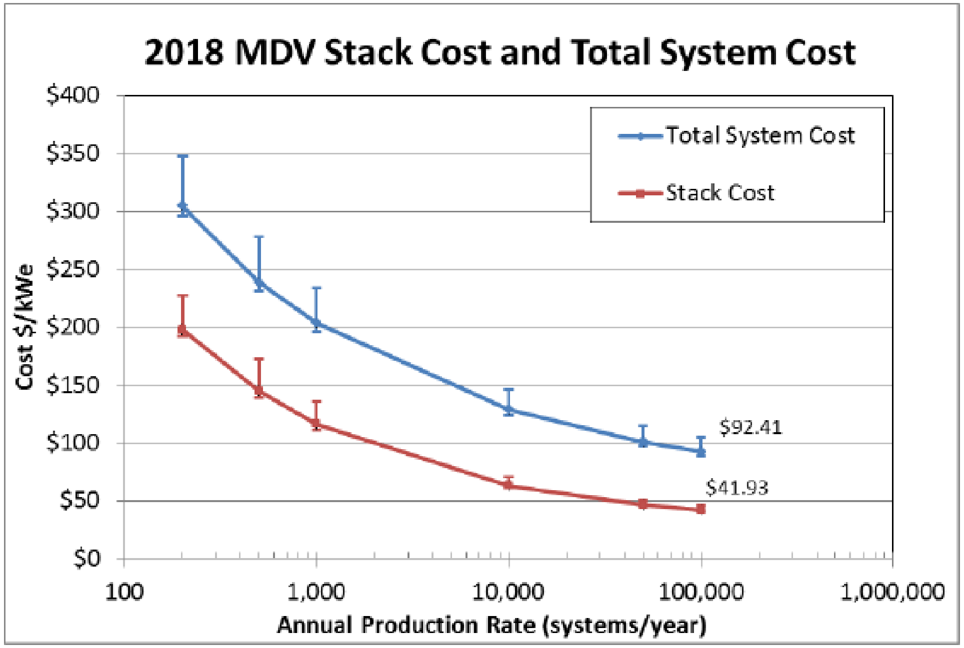
> 20% increase from 2018

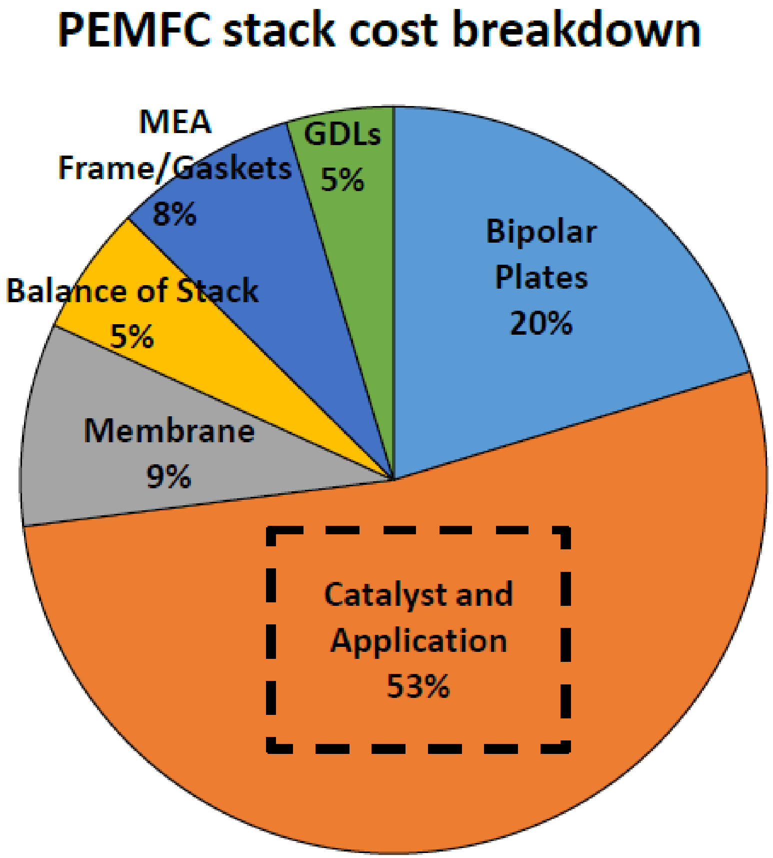
Source: IEA (2020), *Hydrogen*, IEA, Paris, https://www.iea.org/reports/hydrogen

Dr. Sunita Satyapal, HOC (Hydrogen Online Conference), Mission Hydrogen-October 8, 2020

MDV Cost Analysis Highlights R&D Needs

- Based on 2018 cost estimate for 160 kW_{net} system suitable for buses and medium-duty trucks
- High-volume manufacturing cost: **$92/kW$_{net}$** (100,000 systems/year)





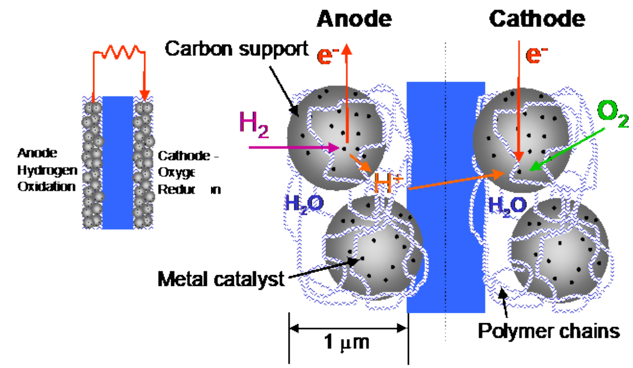
*Manufacturing volume: 100,000 systems/year

Coming in 2019: Heavy-duty fuel cell truck cost analysis

Fuel Cell R&D at Los Alamos

- One of longest running non-weapons programs at LANL (since 1977)
  - **The first fuel cells for transportation program**
- The **current DOE HFTO program grew out** of the original Los Alamos program
- **LANL has the top world-wide citation record in Fuel Cell R&D**
- Cost and durability remain the biggest barriers to commercialization
- Program focus is obtaining fundamental understanding to enable “knowledge-based innovation,” and subsequent materials and process development

LANL Enabling Breakthrough Thin Film Electrode



An electrochemically active reaction site must have reactant access to catalyst, available electronic and ionic conduction paths, and manage water

US Patents #4,876,115, #5,211,984 and #5,234,777

LANL’s innovation in fuel cells technology has played a critical role in the technical viability of fuel cell stacks for FCEVs.

→ Every Fuel Cell Vehicle relies on technology developed at LANL

LANL Program: PEMFC Materials Emphasis

Component level research in all PEMFC relevant areas

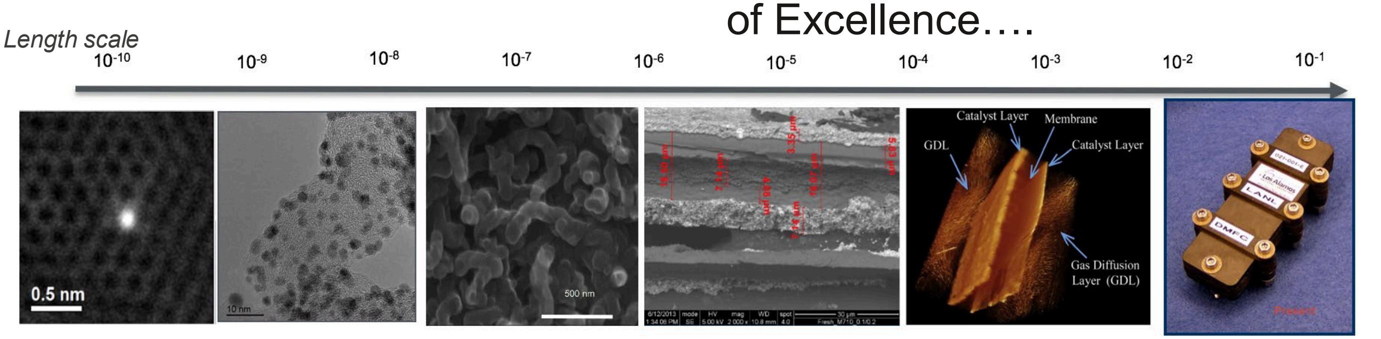
- **LANL Currently Leads Projects That Focus on Stack Components**
  - *M^2FCT (Million Mile Fuel Cell Truck)*
  - *ElectroCat 2.0 Consortia (PGM-free electrocatalysis)*
  - *Low-PGM Electrocatalysis*
  - *Electrode and MEA Design (Membrane Electrode Assembly)*
  - *Alternative membranes (Alkaline, High Temperature)*
  - *Water transport (Novel GDL Materials)*
  - *Hydrogen Safety Codes & standards; sensors; fuel quality*
  - *Miniature Fuel Cell Stacks (NNSA funded)*

Related Projects:

- Reversible Fuel Cells and Water Electrolysis
- Energy Storage (Flow Batteries/Flow Cells)

Prior projects and capabilities include:

- Alternative Fuel Cells: DMFC and DDMEFC
- Bipolar Plates
- Impurity effects on fuel cell performance
- On-board H_2 Production, H_2 Storage Center of Excellence….



FeN_4 PGM-FREE Active site | 13.5 wt% Pt surface loading | Electropolymerized PPy nanowires | MEA cross-section of electrode layers | 3D Component Tomography | Single-Cell, small stack testing

DOE recognizes LANL as a critical capability to advance fuel cell performance and durability

Fuel cell system targets set to be competitive with ICEVs.

Durability <u>and</u> Cost are the primary challenges to fuel cell commercialization and must be met concurrently

MPA-11 is also testing a mini fuel cell for a stockpile application and collaborating with GS to support potential cubesat missions

FUEL CELL FCPAD PERFORMANCE & DURABILITY

Rod Borup is Director of the Consortium for Fuel Cell Performance and Durability

Los Alamos NATIONAL LABORATORY
Argonne NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
BERKELEY LAB
OAK RIDGE National Laboratory

5-Year Multi-lab consortium

ElectroCat
Electrocatalysis Consortium

Project Focus: PGM-free catalysts for automotive fuel cells

Los Alamos NATIONAL LABORATORY
Argonne NATIONAL LABORATORY

Piotr Zelenay is co-director of the new consortium: ElectroCat – part of the DOE Energy Materials Network (EMN)

Zero-Emission Vehicles

- Norway 2025, Denmark 2030, Netherlands 2030, Sweden 2030, India 2030, France 2040, United Kingdom 2040, Sri Lanka 2040, China (no date set), Canada - British Columbia (2040). In the United States, municipalities such as Seattle (2030) and Los Angeles (2030) have announced bans. Now California.

June 2020

The New York Times

New Rule in California Will Require Zero-Emissions Trucks

More than half of trucks sold in the state must be zero-emissions by 2035, and all of them by 2045.

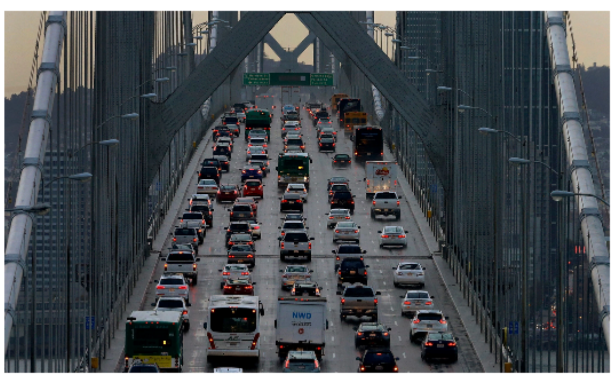
An Amazon warehouse in the Inland Empire of California last year. Philip Cheung for The New York Times

September 2020

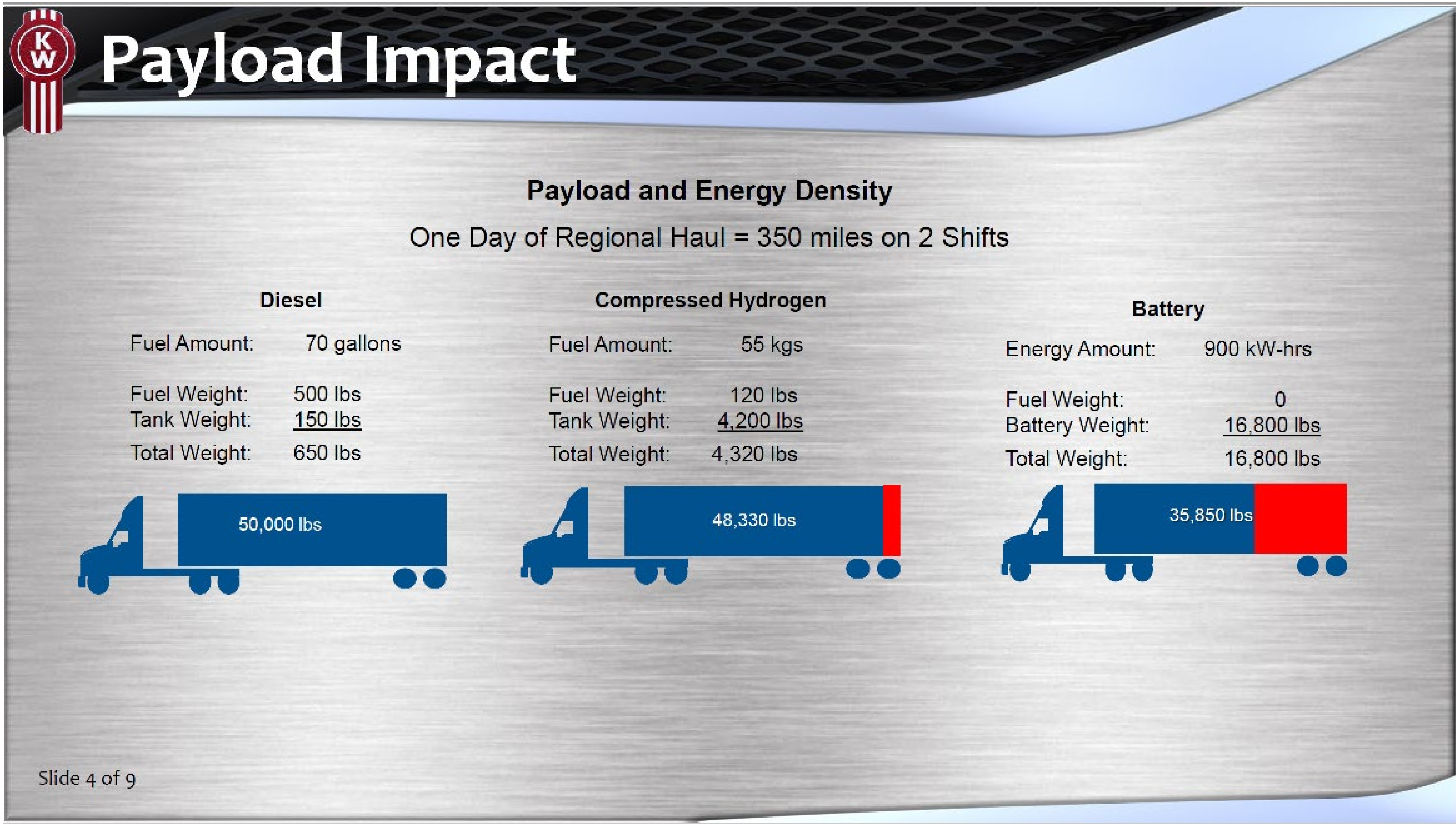
The New York Times

California Plans to Ban Sales of New Gas-Powered Cars in 15 Years

The proposal would speed up the state's efforts to fight global warming at a time when California is being battered by wildfires, heat waves and other consequences of climate change.



Transportation remains California's largest source of planet-warming emissions, accounting for roughly 40 percent of the state's greenhouse gases from human activity. Ben Margot/Associated Press



Brian Lindgren, **Kenworth Truck Company,** California Hydrogen Business Council (CHBC)**,** April 14, 2020

Target Comparison between Light-Duty and Heavy-Duty

Table 1. Technical Targets for Automotive-Scale (80 kW_e net Fuel Cell System Operating on Hydrogen[a]

Characteristic	Units	Status	2020 Target	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	$/$kW_e$	45 [e]	40	35
Cold start-up time to 50% of rated power				
@ -20°C ambient temp	sec	20 [f]	30	30
@ +20°C ambient temp	sec	<10 [f]	5	5
Durability in automotive load cycle	hours	4130 [g]	5,000	8,000
Unassisted start from [h]	°C	-30 [i]	-30	-30

Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

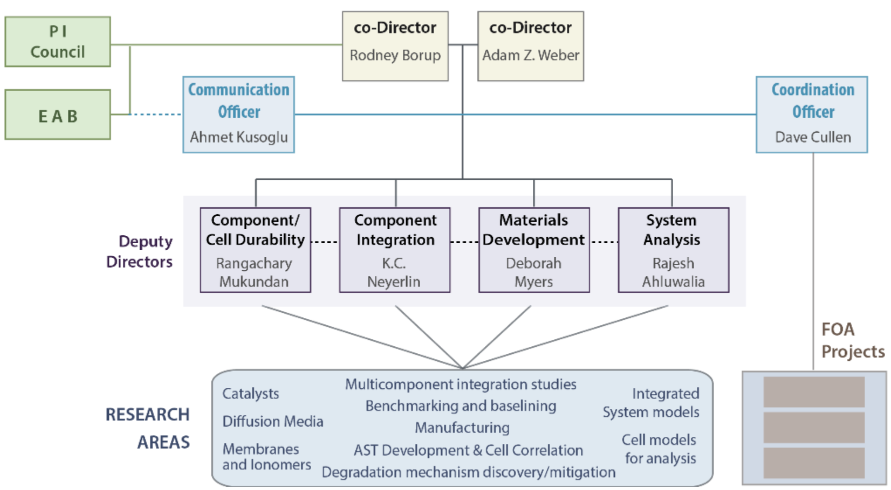
Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	**25,000**	**30,000**
Fuel Cell System Cost[1,3,4]	$/kW	**80**	**60**
Fuel Cell Efficiency (peak)	%	**68**	**72**
Hydrogen Fill Rate	kg H_2/min	**8**	**10**
Storage System Cycle Life[5]	cycles	**5,000**	**5,000**
Pressurized Storage System Cycle Life[6]	cycles	**11,000**	**11,000**
Hydrogen Storage System Cost[4,7,8]	$/kWh ($/kg H_2 stored)	**9** (**300**)	**8** (**266**)

Million Mile Fuel Cell Truck (M^2FCT)

5 year, $10M per year Consortium ($50M total)

Goal 1:	Develop predictive models for cells and systems and exercise them to define real-world operation and component and assembly targets.
Goal 2:	Develop materials that enable high efficiency and durable performance
Goal 3:	Evaluate rationally designed multicomponent MEAs comprised of tailored interfaces and components that exhibit transformational cell-level performance and efficiency.
Goal 4:	Realize and interrogate ensembles of materials to elucidate and mitigate degradation.

Overall Target: 2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test

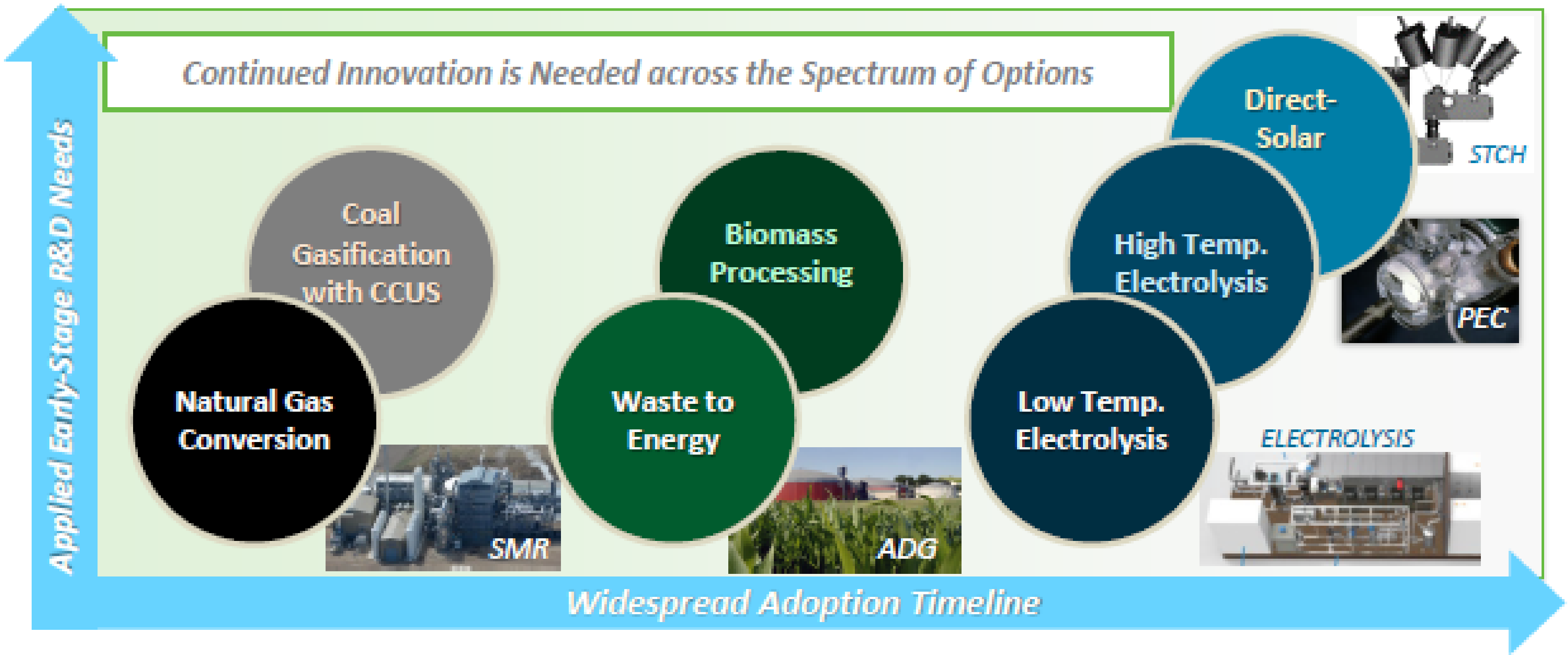


New Heavy Duty Project/Partners

Domestically Manufactured Fuel Cells for Heavy-Duty Applications

Membranes for Heavy-Duty Applications

Strategies: H_2 Production R&D



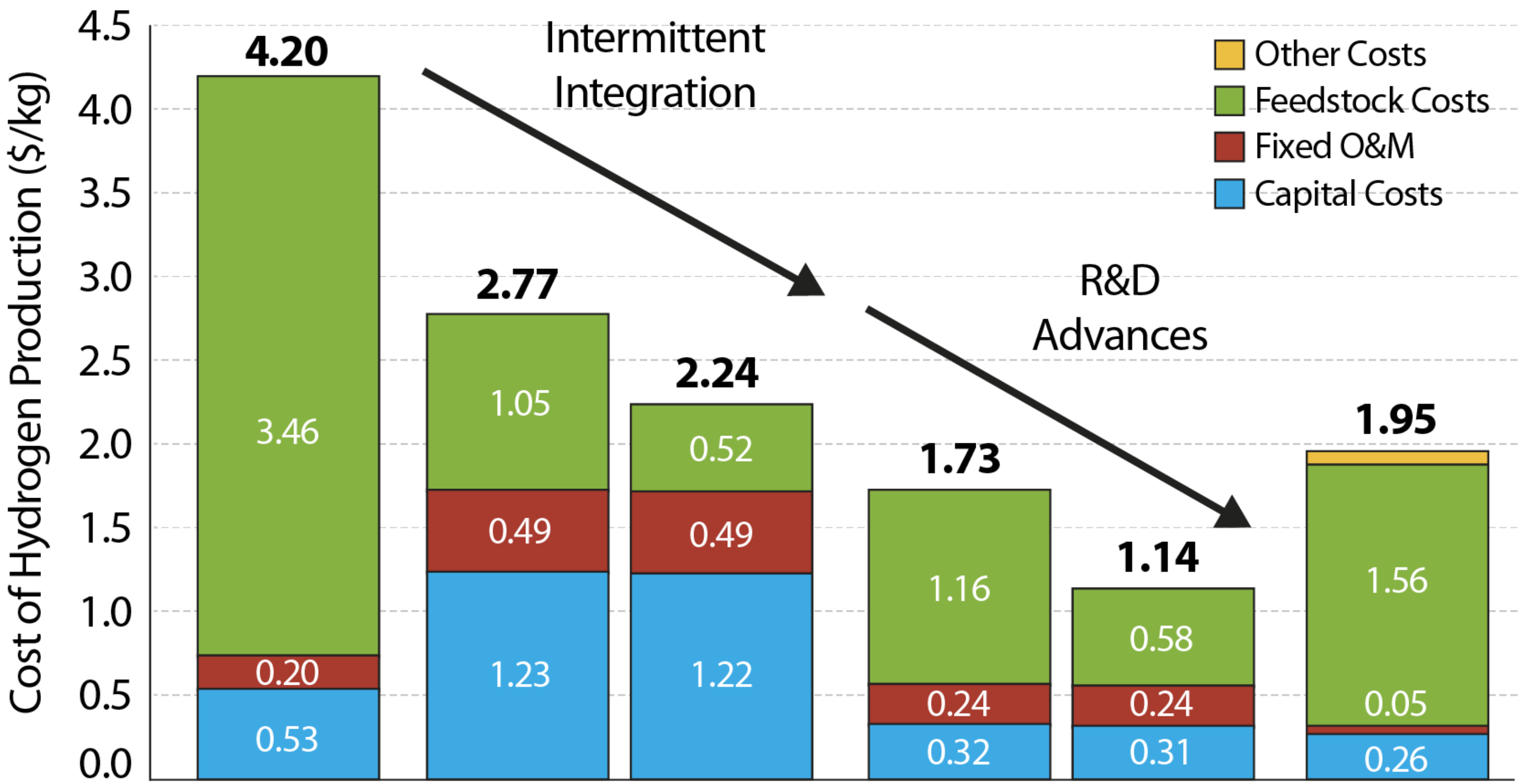
Innovative Concepts: Fossil Fuels/Waste/Biomass

- Natural gas and coal conversion with options for CCUS and value-added byproducts
- Industrial and biomass waste conversion providing clean-up value
- Biogas reforming, fermentation, & other innovative concepts

Advanced Water Splitting (AWS)

- Low temperature electrolysis, both grid and off-grid
- High-temperature electrolysis, including integration with nuclear and solar
- Emerging direct solar options, including solar thermochemical and photoelectrochemical

Improving Economics of Renewable Electrolytic H_2

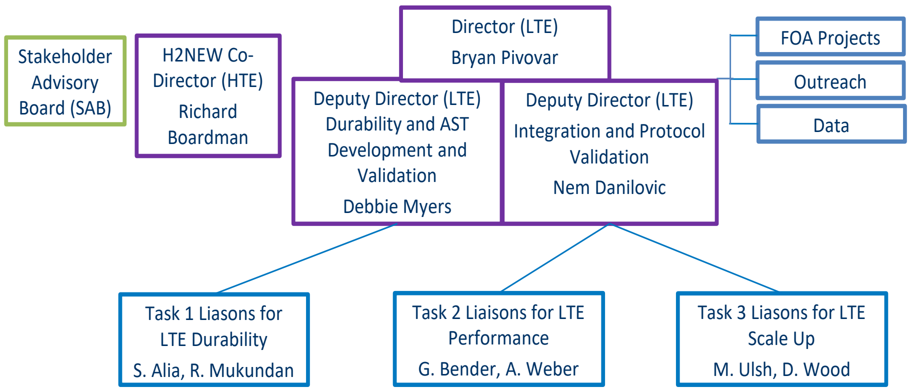


Capacity Factor	97%	40%		40%		0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh	¢1/kWh	¢2/kWh	¢1/kWh	
Capital Cost	$400/kW	$400/kW		$100/kW		
Efficiency (LHV)	66%	66%		60%		
	Electrolyzer					**SMR**

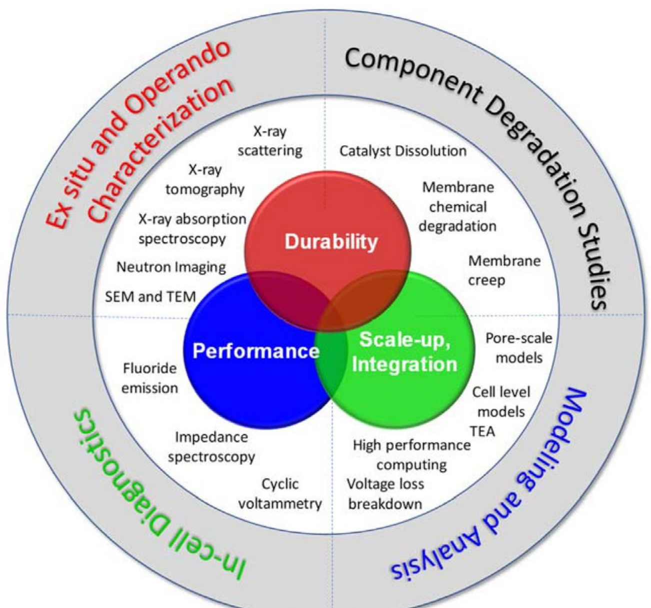
H2NEW

GOAL: Address components, materials integration, and manufacturing R&D to enable manufacturable electrolyzers that meet required cost, durability, and performance targets, simultaneously, in order to enable $2/kg hydrogen.

Organization Structure



Tasks

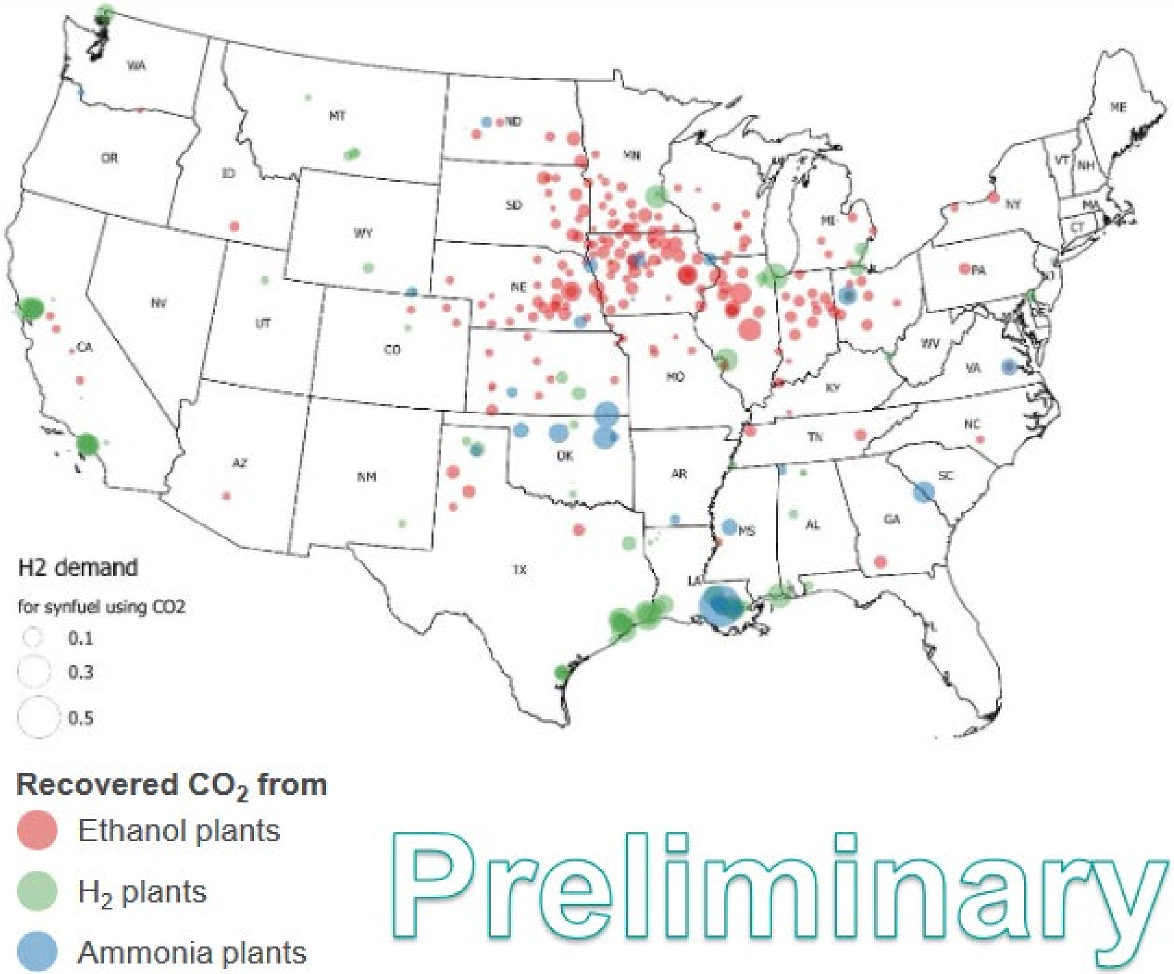


People / Expertise

LTE PI	Lab	Expertise in H2NEW
Bryan Pivovar	NREL	Director (LTE) H2NEW, degradation mechanisms, MEA fabrication, membranes, benchmarking
Debbie Myers	ANL	Deputy Director for Durability Thrust. In situ catalyst degradation studies, in situ and operando X-ray studies of materials, inks, electrodes, and cells
Nemanja Danilovic	LBNL	Deputy Director for Performance and Integration Thrusts. Electrified interfaces engineering and characterization, component characterization, operando x-ray characterization
Rajesh Ahluwalia	ANL	Cell modeling, system and technoeconomic analysis, performance and durability analysis, degradation mechanisms, electrode structure characterization
Siddharth Komini Babu	LANL	Operando neutron imaging, MEA integration, contaminants
Rangachary Mukundan	LANL	ASTs, degradation mechanisms, electrode design, MEA integration, contaminants
Ahmet Kusoglu	LBNL	Ionomer structure/function relationships, mechanical properties, x-ray studies
Adam Weber	LBNL	Multiscale modeling, component characterization, ink interactions
Shaun Alia	NREL	ASTs, degradation mechanisms, electrocatalysis, MEA integration
Guido Bender	NREL	Benchmarking, advanced diagnostics, PTL, MEA integration
Mark Ruth	NREL	Systems and technoeconomic analysis
Mike Ulsh	NREL	Roll to roll, ink studies, electrode fabrication, scale-up
Dave Cullen	ORNL	Ex-situ characterization, advanced microscopy
David Wood	ORNL	Roll to roll, electrode fabrication, water transport

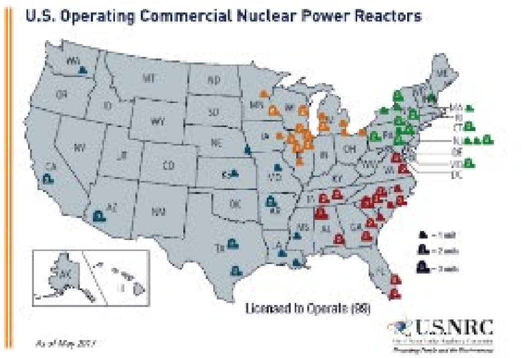
14 MMT POTENTIAL H_2 DEMAND WITH 100MMT CONCENTRATED CO_2 ANNULAY – *Accomplishment*

***Assumption: stoichiometric CO_2/H_2 mole ratio of 1:3**

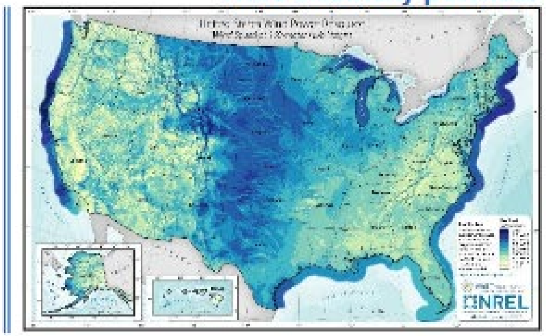


Preliminary

Installed nuclear plants



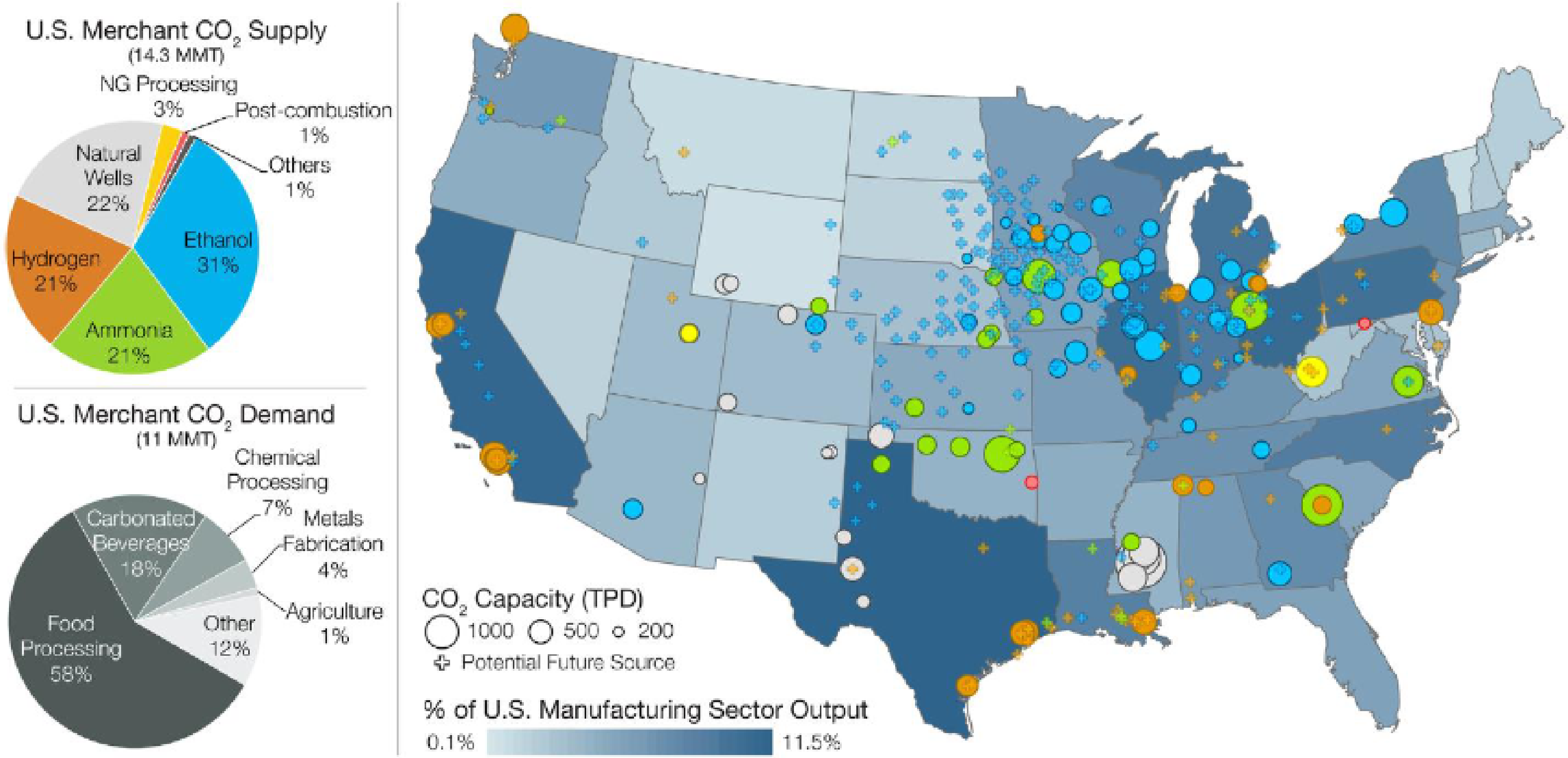
Wind electricity potential



Solar electricity potential

POTENTIAL H_2 DEMAND FOR SYNTHETIC HYDROCARBON PRODUCTION FROM CONCENTRATED CO_2 SOURCES – *Approach*

- Considered 100 million MT of concentrated CO_2 sources (out of total~ 5 GT CO_2)
  - 44 million MT from ethanol plants
    - ✓ Current CO_2 supply capacity of 14 MMT, and market demand of 11 MMT
  - Remainder from hydrogen SMR (refineries) and ammonia plants



Source: Supekar and Skerlos, ES&T (2014)

Hydrogen Safety Sensors

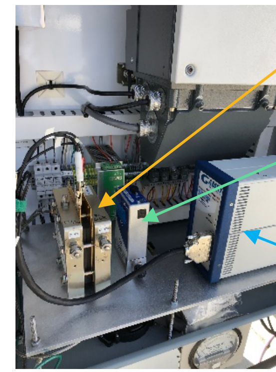
Electrochemical HCD technology

- Expensive
- Calibration intensive
- Sensitive to ambient environment
- Does not necessarily measure fuel quality delivered to customer
- H2F system suffers from continuous drift

Currently: Fuel quality must be measured using expensive analytical instrumentation and situated inside refrigerated enclosures; e.g. NDIR or laser spectroscopy and not in real-time.

LANL Field testing new HCD technology at H2F: 2018-2019

- 1.5 year field trials test
- Holds calibration for more than a year.
- Negligible baseline drift.
- Detects CO and H_2S at SAE J2719 standard.
- Expected to measure any contaminant that poisons a fuel cell

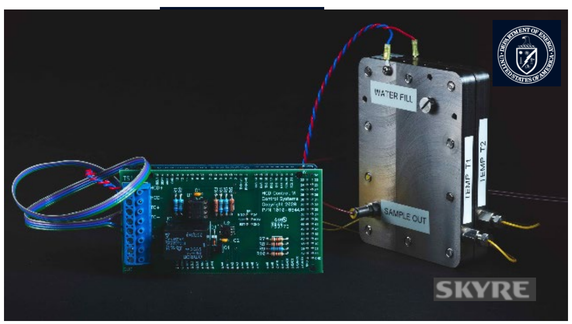


LANL HCD module ~ $5K

MKS mass flow controller ~$1.5K

Gamry Reference 600 Potentiostat $17.5K

FY2020-21 DOE TCF Project



Present *retail materials cost* of the HCD system has been reduced to less than $1200 from $24,000 including a bi-polar Peltier temperature control system.

Hydro Contamination

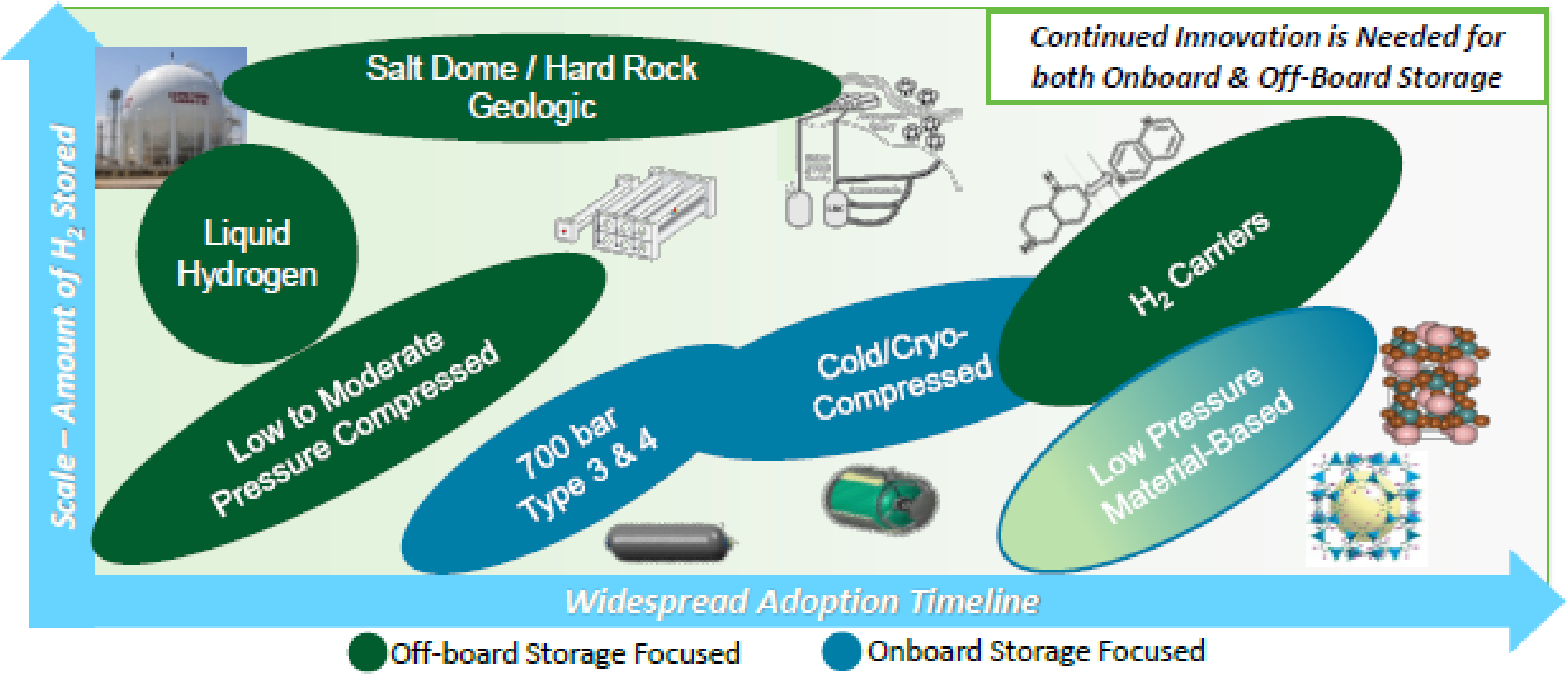
Skyre and H2Frontier

2020 R&D 100 FINALIST

Protecting the future of zero-emission fuel cell energy

Eric Brosha
Chris Romero
Mahlon Wilson
R. Mukundan
Cortney Kreller
Tommy Rockward

Strategies: H_2 Storage R&D



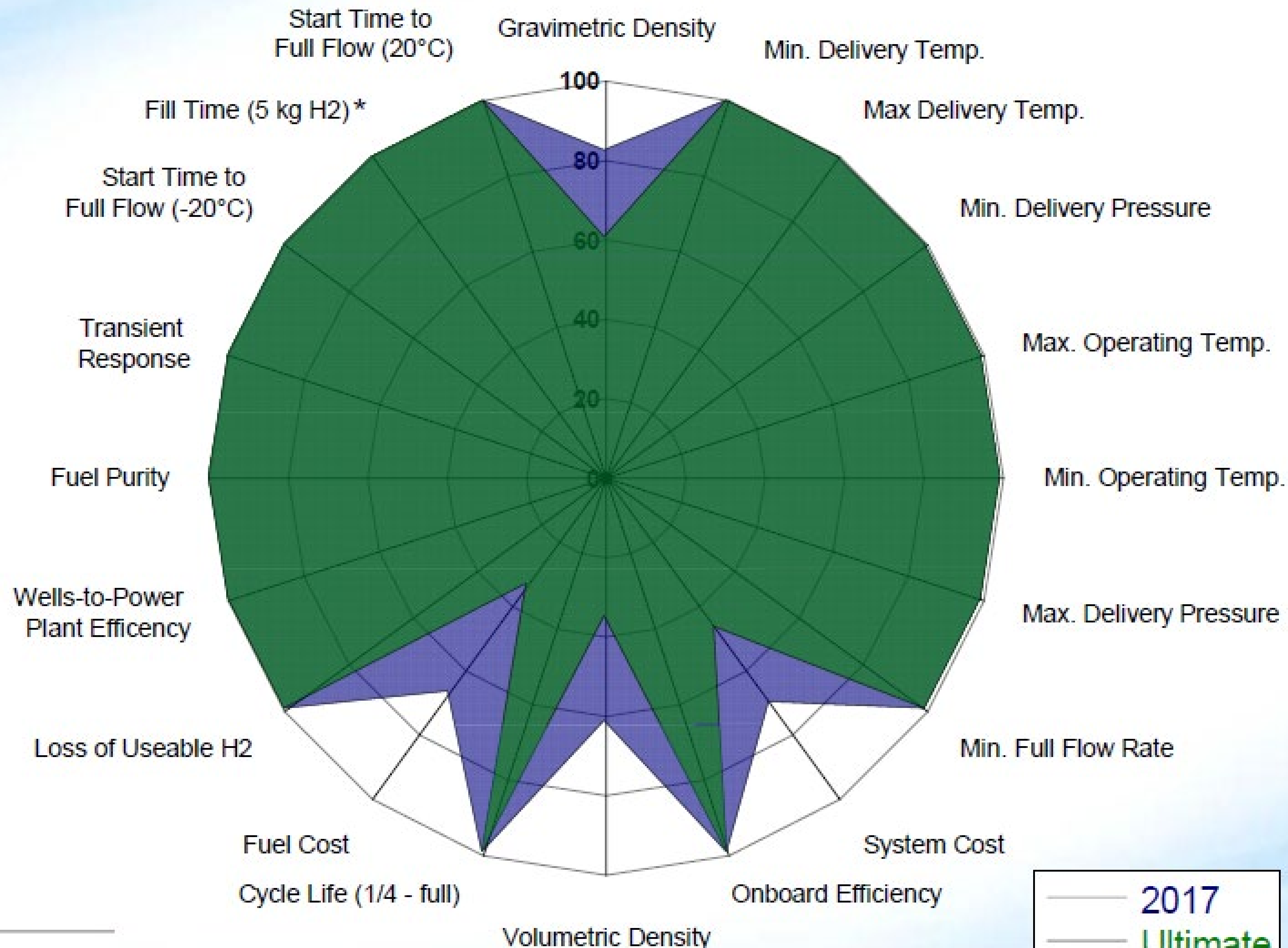
Off-Board Focus Areas

- H_2 carriers that provide advantages for bulk storage and transport
- Baseline bulk storage analysis to understand needs and identify technology gaps
- Improved safety, reliability, and cost

Onboard Focus Areas

- Low-pressure, near-ambient temperature material-based storage
- Materials with improved capacity, kinetics, reversibility, and cost
- Lower-cost, high-strength carbon fiber

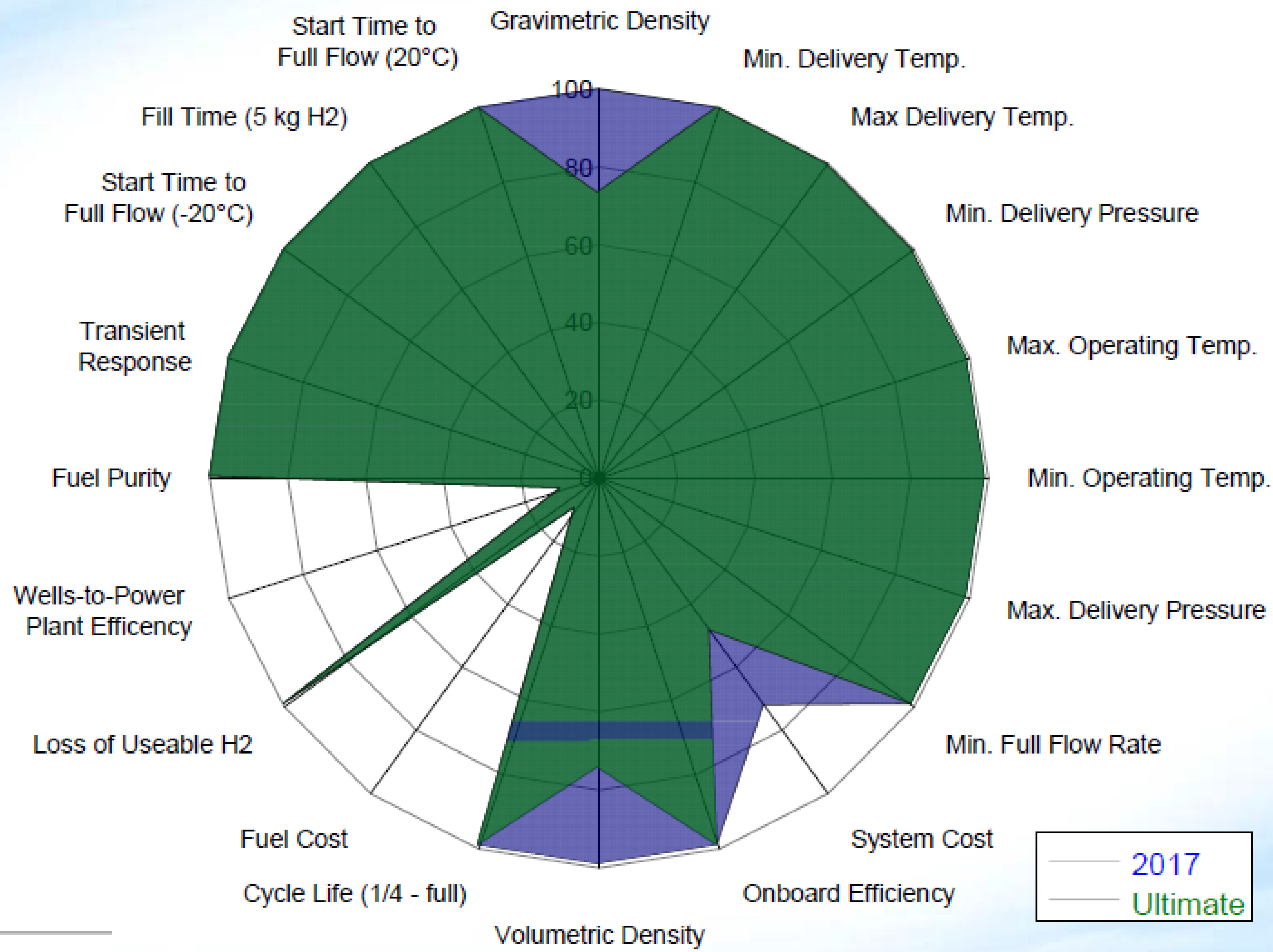
700 bar Compressed Hydrogen-*Commercialized Technology*



HSECoE

* *Estimated fill times for Toyota FCHV ~ 5 min (5.8 kg H_2?), Hyundai Tucson ~ 10 min (5.8 kg H2)*

7.8 wt. % Chemical Hydrogen Storage Material

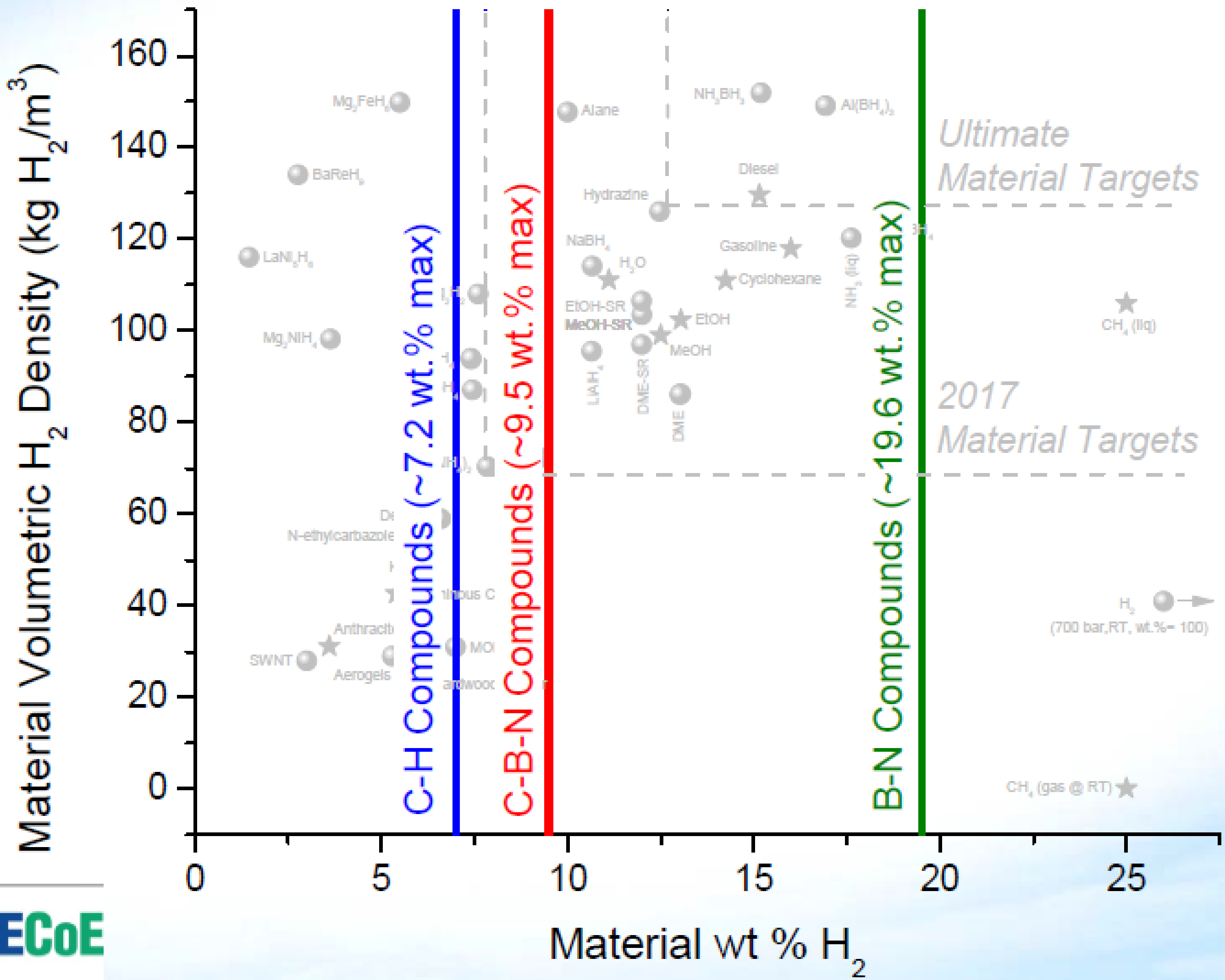


HSECoE

ECoE estimates based on a neat liquid with 7.8 wt. % usable H2 and idealized system design of mass 30.6 kg and 35 L

State-of-the-Art

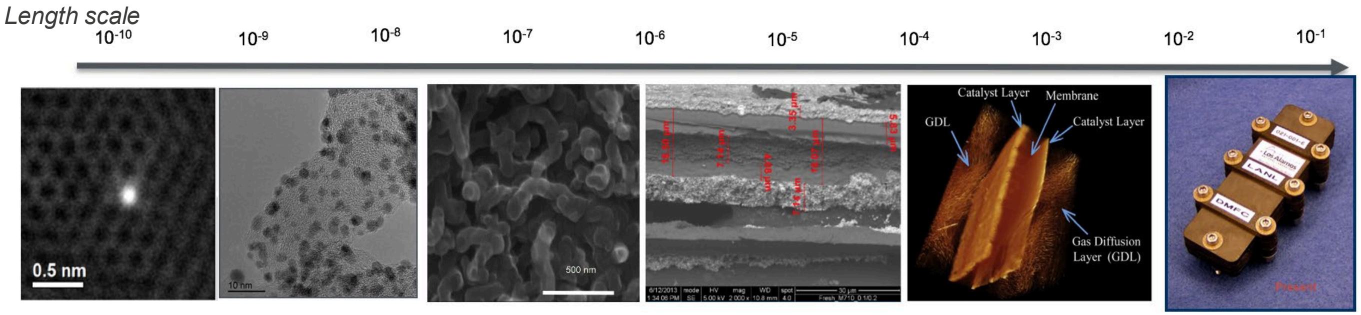
C-H Compounds: reversible conjugated diene systems (7.2 wt. % theoretical, 7.2 wt. % observed)
C-B-N Compounds: reversible CBN backbones (9.5 wt. % theoretical, ~4.5 wt. % observed)
B-N Compounds: 19.6 wt.% theoretical, ~15.5 wt. % observed)
★ *Values denote maximum theoretical wt. % H_2 (i.e., all hydrogen removed)*
Material targets derived from the idealized fluid-phase system design



HSECoE

LANL Hydrogen & Fuel Cell Program

- **LANL Currently Leads Projects That Focus on Stack Components**
  - *M^2FCT (Million Mile Fuel Cell Truck)*
  - *ElectroCat 2.0 Consortia (PGM-free electrocatalysis)*
  - *Materials: advanced membranes, catalysts, ….*
- **LANL Involved in Low-Temp Electrolysis (H2NEW)**
  - *Lead durability effort*
  - *Materials: advanced membranes, catalysts, ….*
- **LANL led Hydrogen Chemical Storage Center of Excellence**
  - *System leader for Hydrogen Engineering Storage Center of Excellence*



FeN_4 PGM-FREE Active site | 13.5 wt% Pt surface loading | Electropolymerized PPy nanowires | MEA cross-section of electrode layers | 3D Component Tomography | Single-Cell, small stack testing

Supplemental

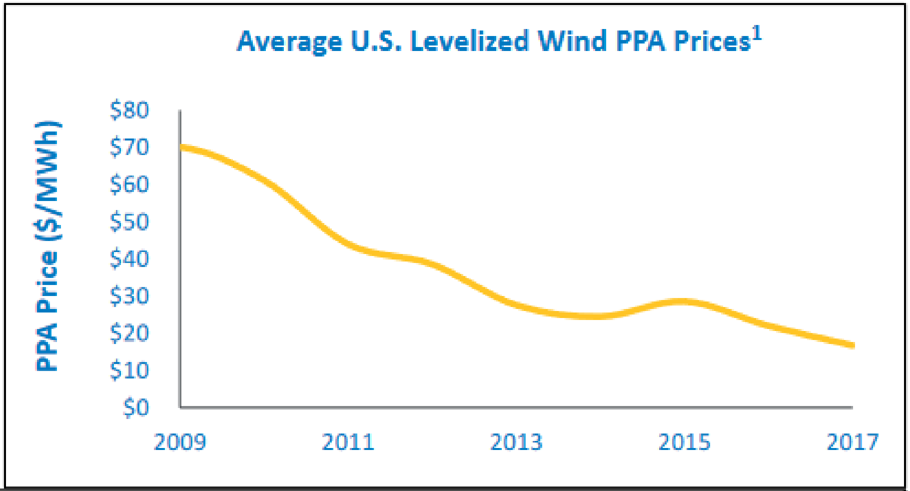
Key Drivers for Evolving Energy System

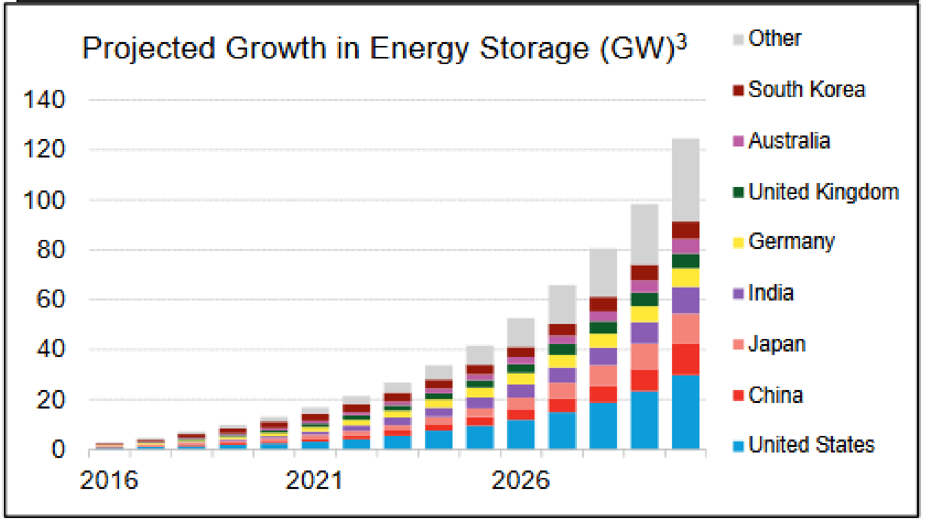
Increasing low-cost, renewable variable electricity

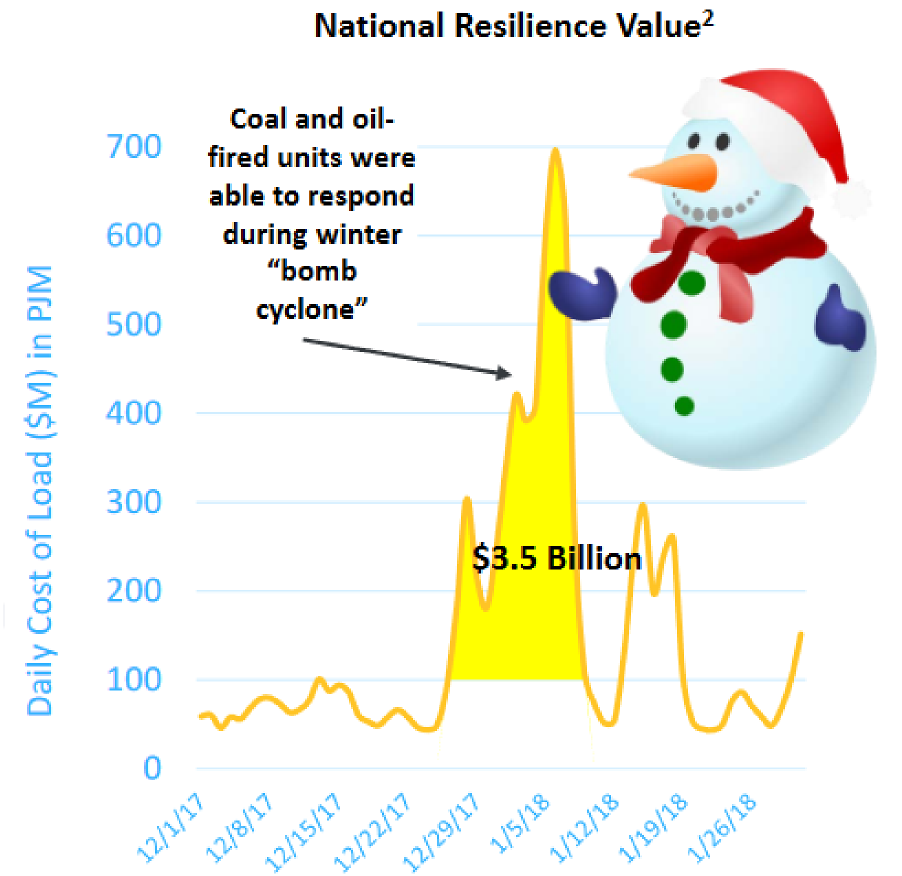
Rapid growth in energy storage

Competitive Manufacturing

Energy System Security/Resilience





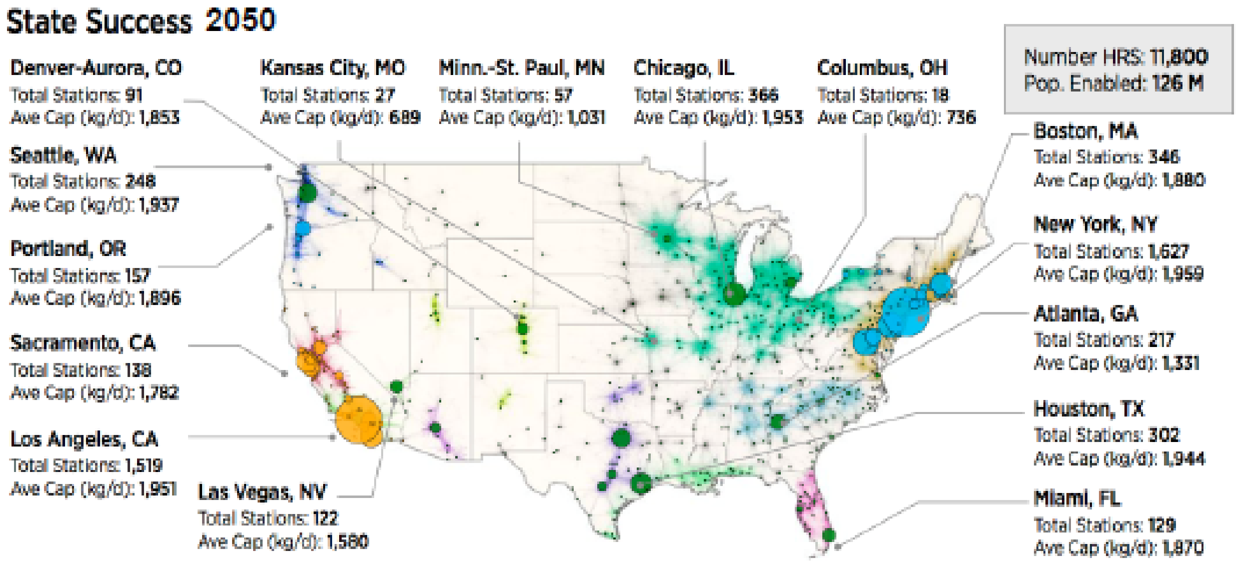


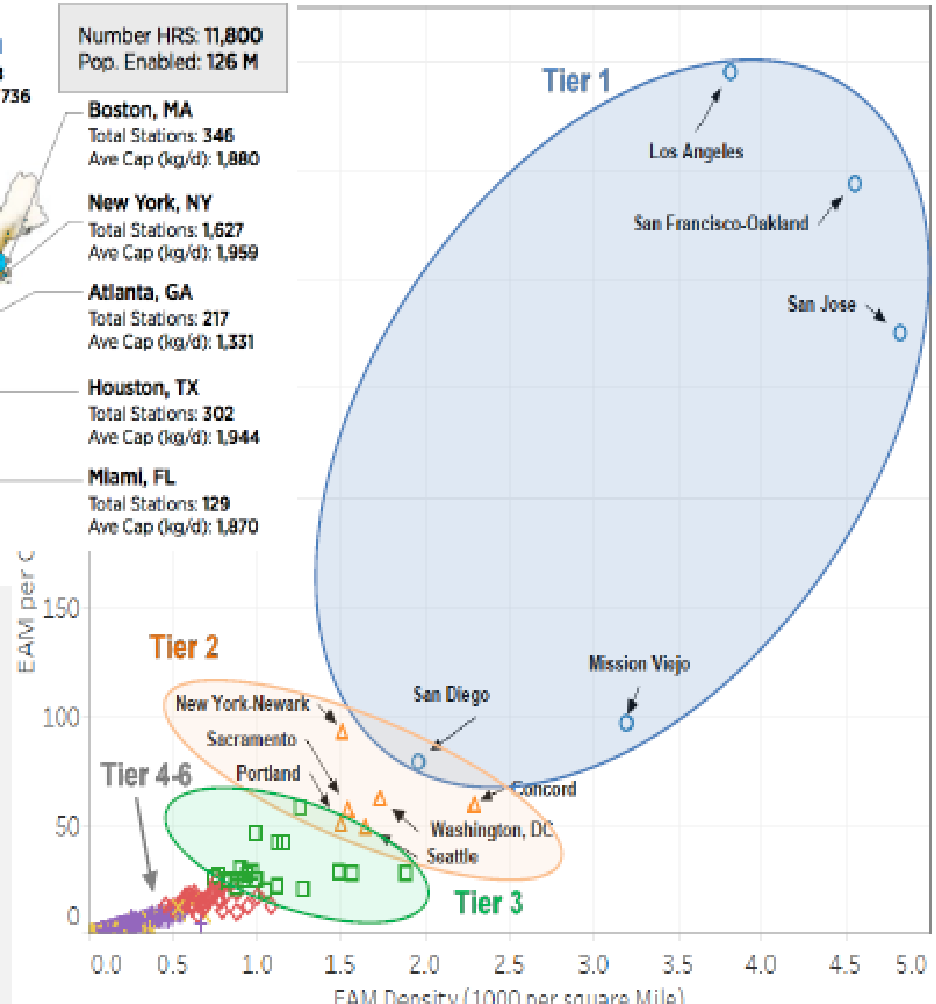
1. Lawrence Berkeley National Laboratory, https://emp.lbl.gov/wind-technologies-market-report
2. National Energy Technology Laboratory, https://www.netl.doe.gov/energy-analyses/temp/ReliabilityandtheOncomingWaveofRetiringBaseloadUnitsVolumeITheCriticalRoleofThermalUnits_031318.pdf

3. Source: Sekine, Yayoi. "2017 Global Energy Storage Forecast". Bloomberg New Energy Finance.

Scenario Analysis for Hydrogen Fueling Station Rollout

Modeling the optimal size and placement of hydrogen stations over time under various scenarios



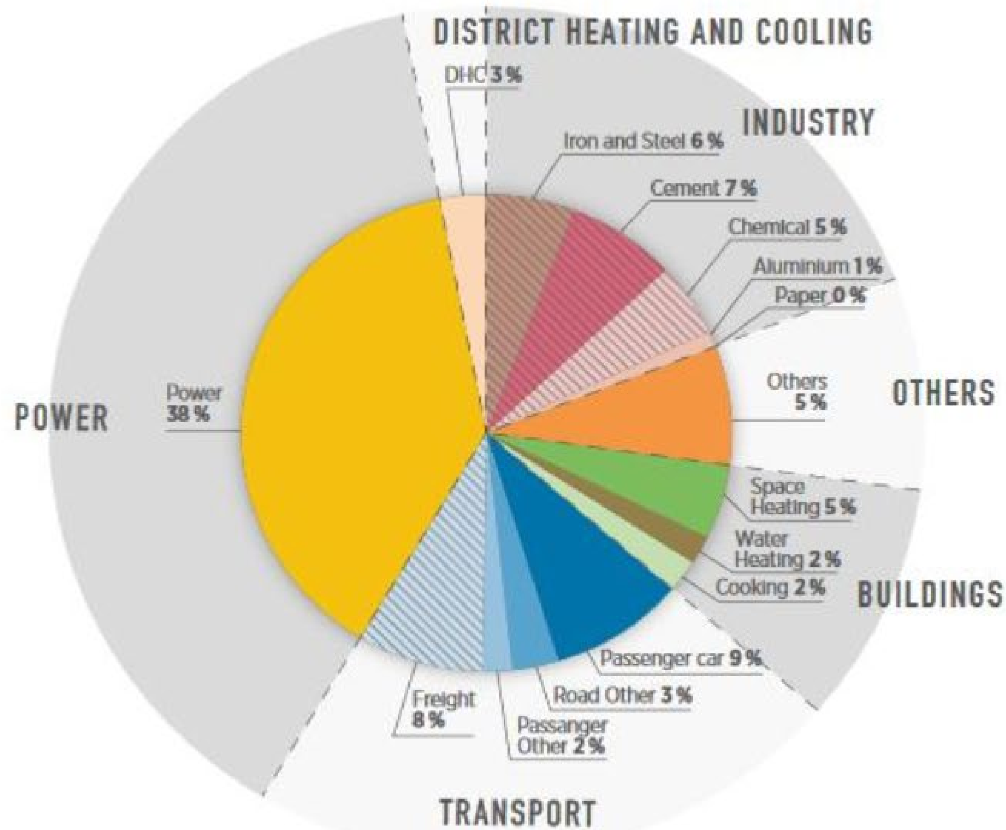


Tiers represent clusters of sequential FCEV introduction, based on **early adopter metrics,** industry input, and geographical considerations.

SERA

NREL

Global Energy Related Carbon Emissions by Sector



Sectors today with no economically scalable option for deep emission reductions

Source: IRENA, 2017a from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

Dr. Sunita Satyapal, HOC (Hydrogen Online Conference), Mission Hydrogen-October 8, 2020

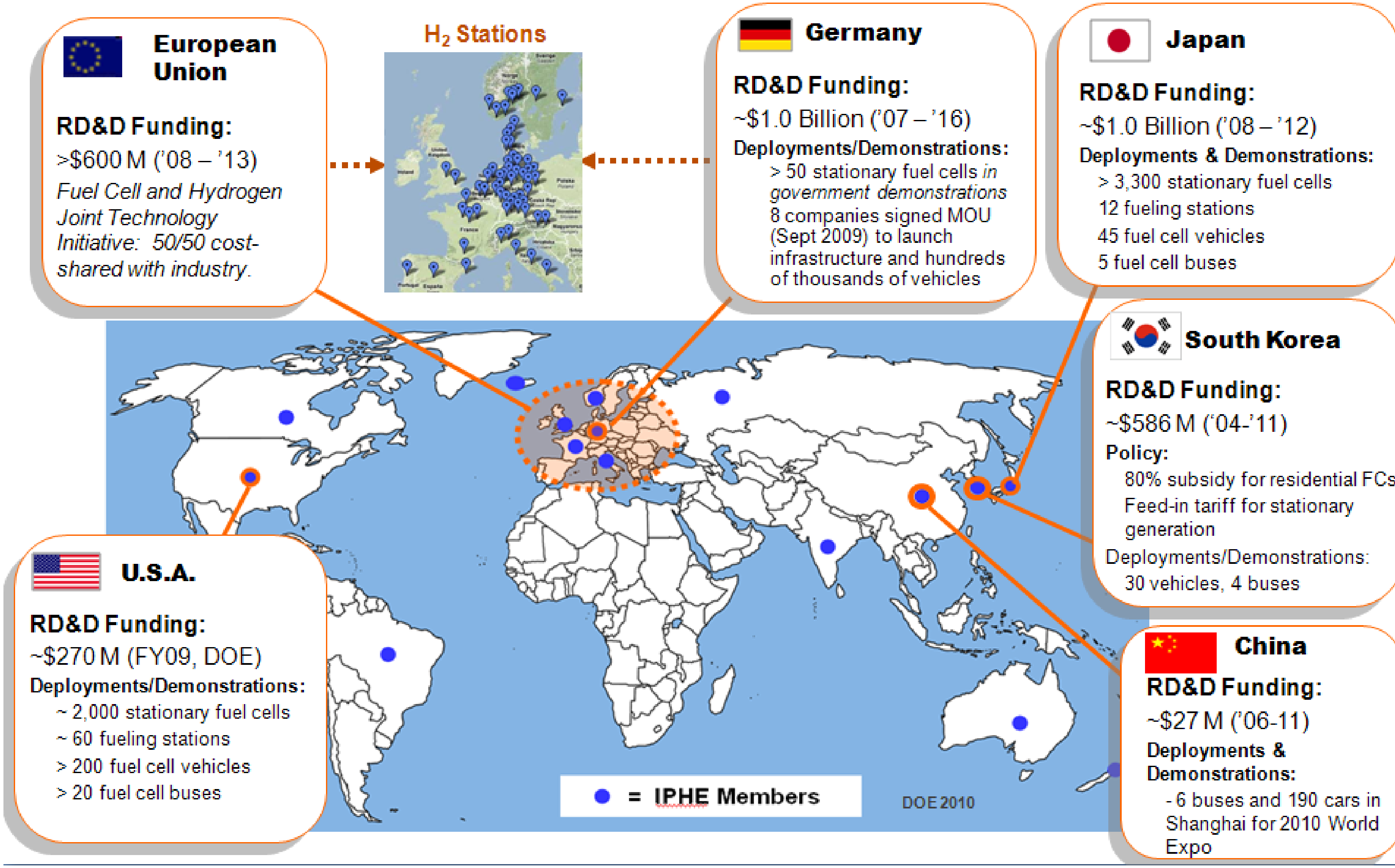
M^{2}FCT Collaborators & Project Support

New Heavy Duty Project/Partners

Membranes for Heavy-Duty Applications

Domestically Manufactured Fuel Cells for Heavy-Duty Applications

Fuel Cells - *Worldwide Developments*

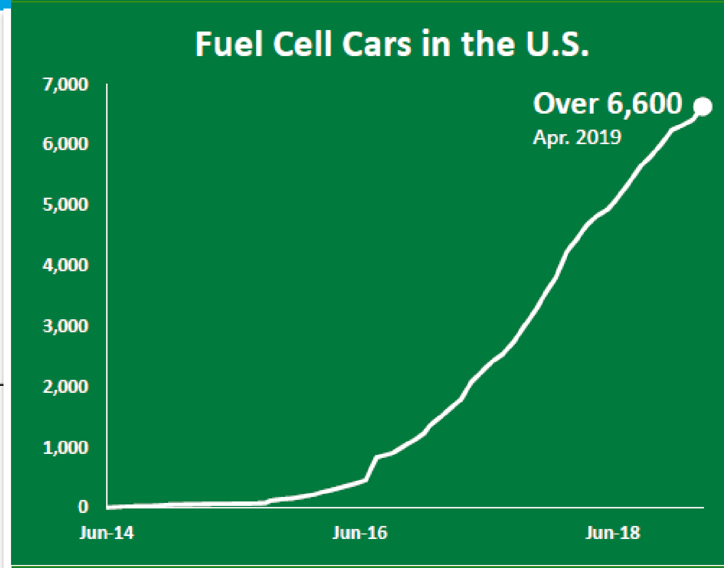


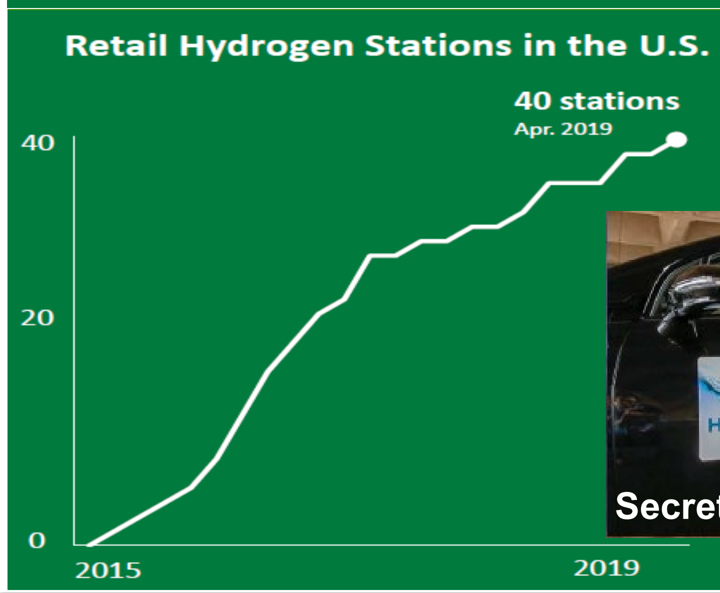
Japanese H2 infrastructure of ~ 200 refilling stations by 2015

China spent ~ Rmb85bn ($12.4bn) supporting fuel cell powered vehicles in 2018: Mix of national and local subsidies.

China has $17 billion worth of announced investments through 2023.

FCEVs are on U.S. Roads Now!





Examples of Applications

- **>240MW** Backup Power
- **>25,000** Forklifts
- **>30** Fuel Cell Buses
- **>40** H_2 Retail Stations
- **>6,600** Fuel Cell Cars

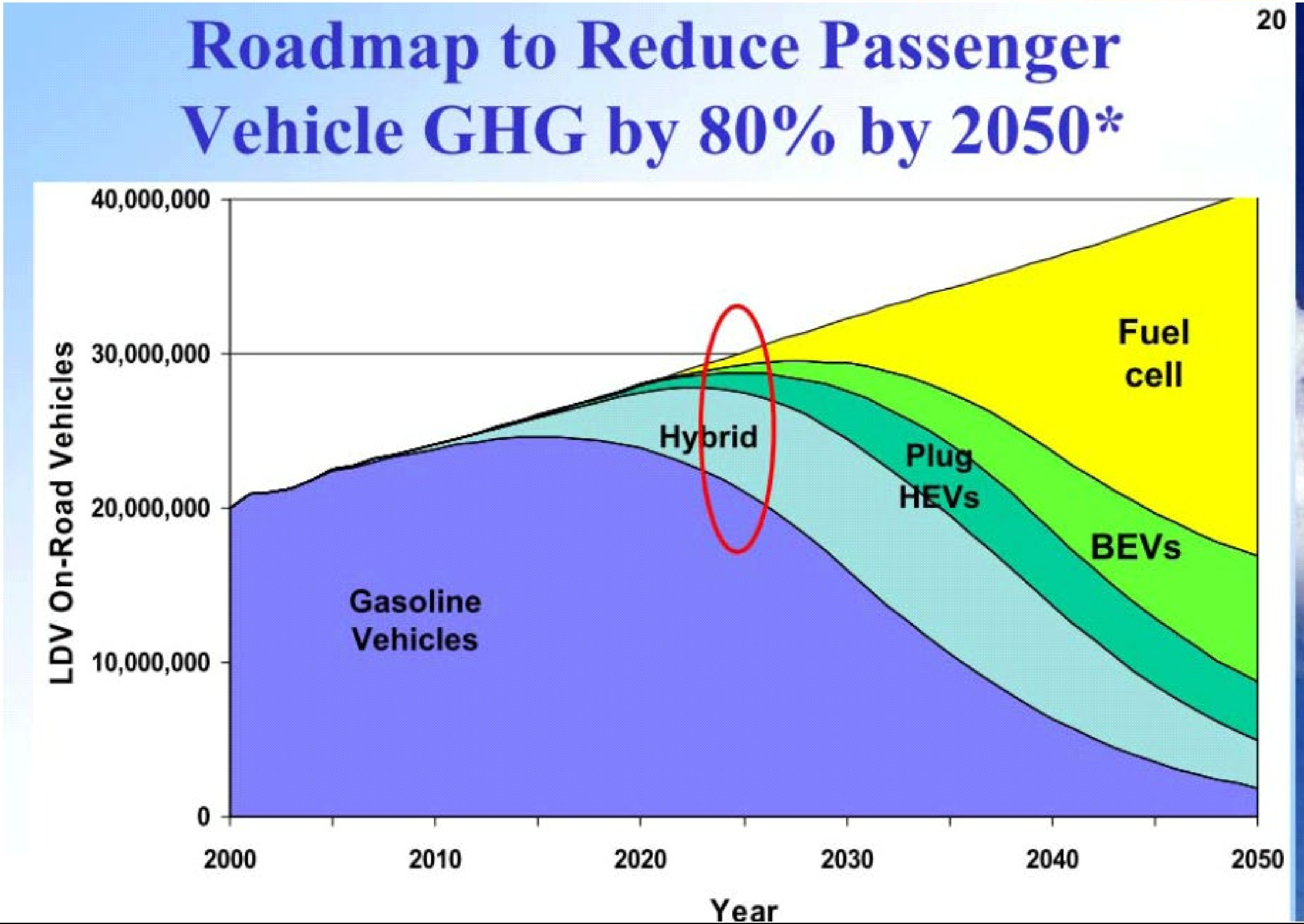
~ Major auto companies have fuel cell vehicle programs including above, plus BMW, Volkswagen, Ford, Honda, Hyundai, ….

Why does it take so long to charge batteries?

Fueling Time Analogy

- Pumping 14 gallons of gasoline in 3 minutes is equivalent to 10 Megawatts of power
- The average hydrogen power flow in 27,000 hydrogen FCEV fueling events monitored by NREL was 1.82 MW
- A home 120V/20A circuit has a maximum power rating of 1.9 kW, which is 5,300 times slower than pumping gasoline and 950 times slower than pumping hydrogen
- A Type-2 240V 40A circuit has 7.7 kW power, or 1,300 times slower than gasoline and 240 times slower than hydrogen.

CARB's Vehicle ROADMAP
(Source Tom Cackette)



Estimated Installed Cost for Hydrogen Fueling Stations

		DOE's H2A Model		
		Single Quantity**	500 units*	
Mobile Refueler***	100 kg/day	$ 1,000,000	$ 243,000	
LH2 Station	400 kg/day	$ 1,682,000	$ 1,071,000	
LH2 Station	1000 kg/day	$ 2,053,000	1285000	

* 500 quantity estimates from DOE H2A for LH2 Stations

** Single quantity estimates extrapolated from DOE H2A model

*** Mobile Refueler estimates from UC-Davis

Graphs for Story Simultaneous.XLS; Tab 'Govt Incentives'; F 56 4/26 /2010

BEV outlet Cost Estimates

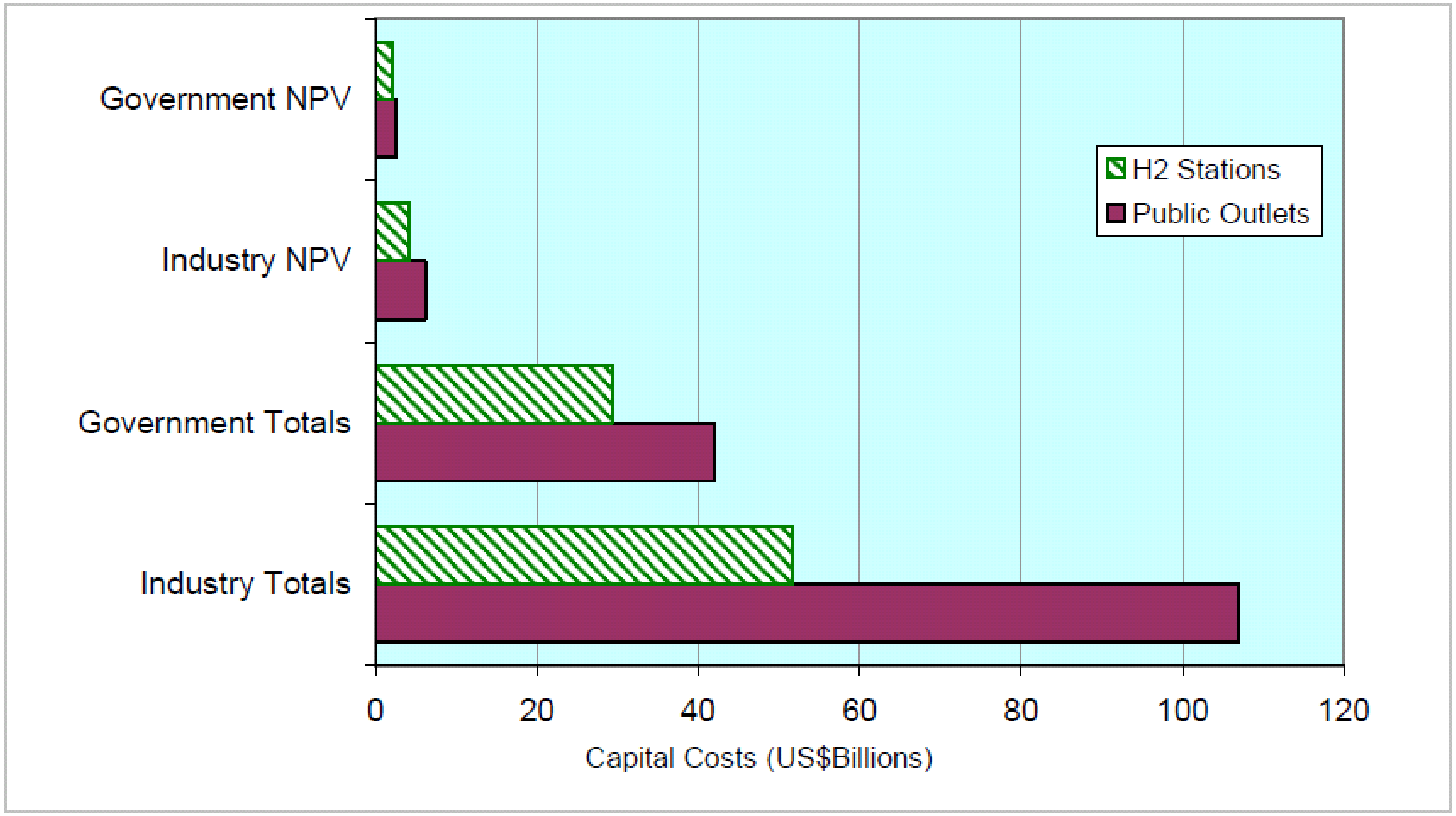
Table 3. Cost estimates for installing electrical outlet boxes or electric vehicle supply equipment (EVSE) to charge vehicle batteries

	Electrification Coalition [7]	Idaho National Laboratory [8]
Type 1 Residential120-Volt EVSE		$833 to $878
Type 2 Residential 220-Volt EVSE	$500 to $2,500	$1,520 to $2,146
Type 2 Public 220-Volt EVSE	$2,000 to $3,000	$1,852
Type 3 public fast charger	$25,000 to $50,000	

Coulomb Technologies: 4,600 Type II (240V) outlets for $37 Million => $8,043 per outlet.

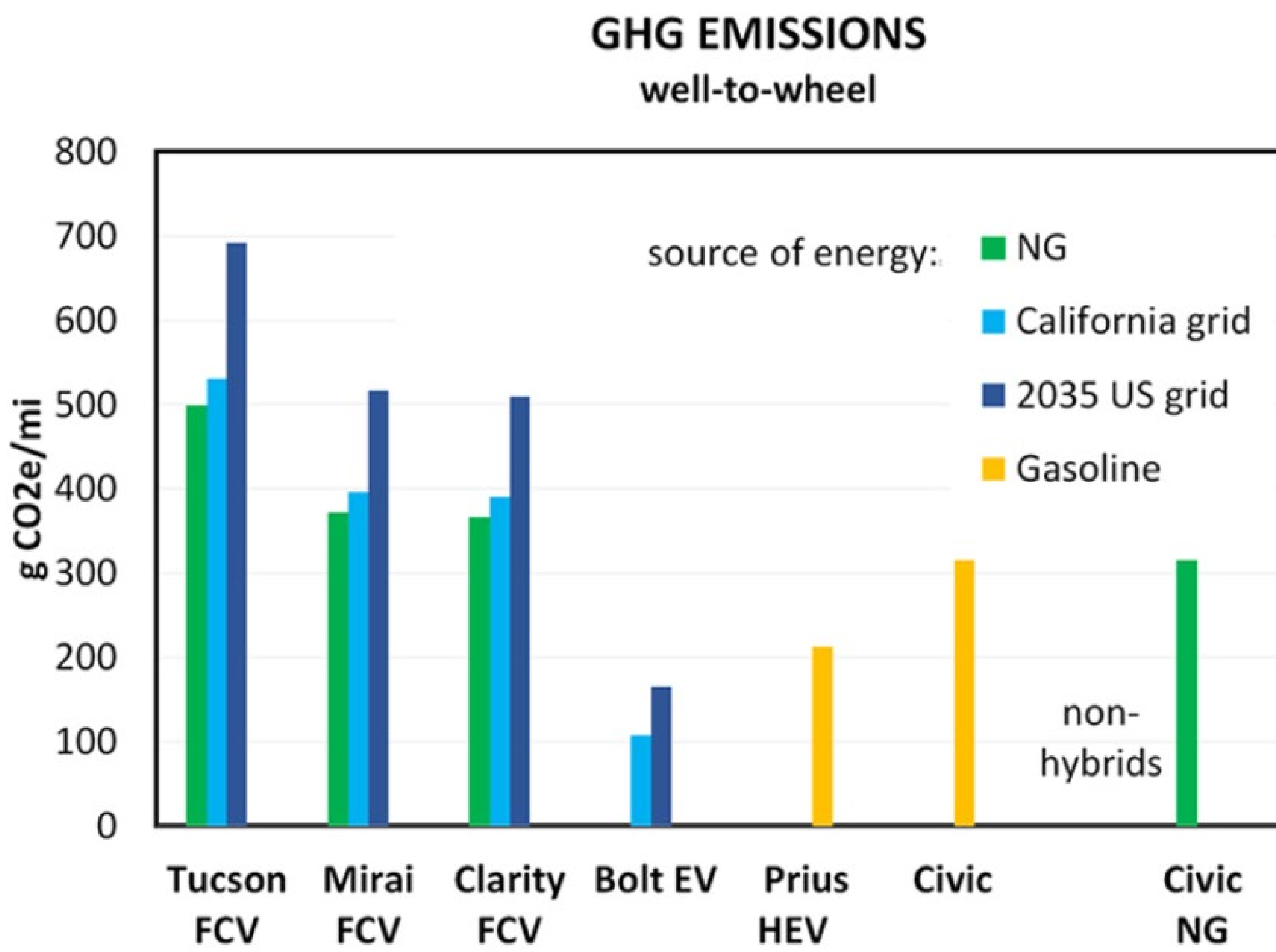
Electrification Coalition Roadmap request for government funding: $120 billion over 8 years or $15 billion per year to install public charging stations

Summary Comparison of Hydrogen infrastructure costs & Public outlet costs through 2056



Graphs for Story Simultaneous.XLS; Tab 'Govt Incentives'; I317 5/6 /2010

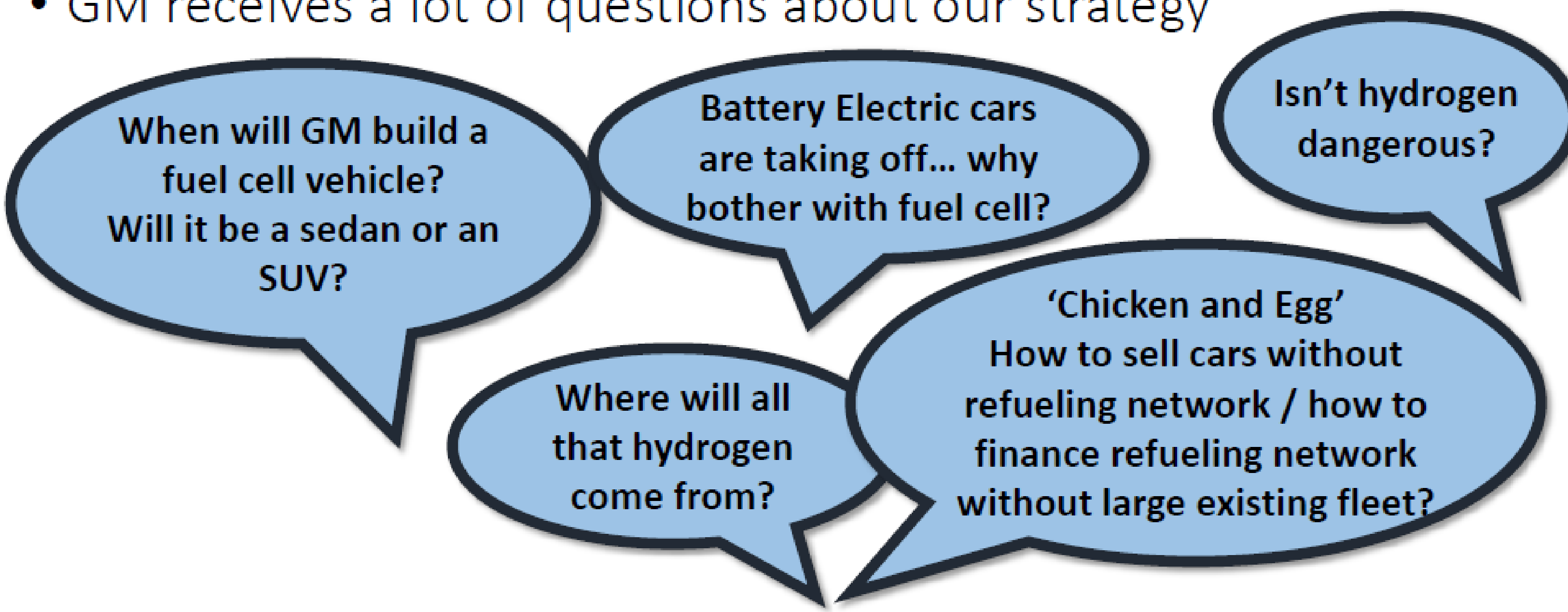
Public charging outlet investments are 2 to 2.6 times more than hydrogen infrastructure investments


GHG EMISSIONS
well-to-wheel
g CO2e/mi
800
700
600
500
400
300
200
100
0
source of energy:
NG
California grid
2035 US grid
Gasoline
non-
hybrids
Tucson FCV
Mirai FCV
Clarity FCV
Bolt EV
Prius HEV
Civic
Civic NG

HYDROTEC
GENERAL MOTORS

Inconsistent Fuel Cell Interest among Automakers

- GM is increasing our commitment to fuel cell technology
- While most major automakers are active in fuel cell, few are committed
- GM receives a lot of questions about our strategy



Kurt Wellenkotter, General Motors, 232rd Meeting of the Electrochemical Society (2017)

HYDROTEC
GENERAL MOTORS

When will GM build a fuel cell vehicle? Will it be a sedan or an SUV?

Early 2020's

Stay tuned!

Battery Electric cars are taking off... why bother with fuel cell?

Fuel cell and BEV have different strengths that complement each other

Isn't hydrogen dangerous?

All fuels requires care

Where will all that hydrogen come from?

New channels and potentially new sources

'Chicken and Egg'
How to sell cars without refueling network / how to finance refueling network without large existing fleet?

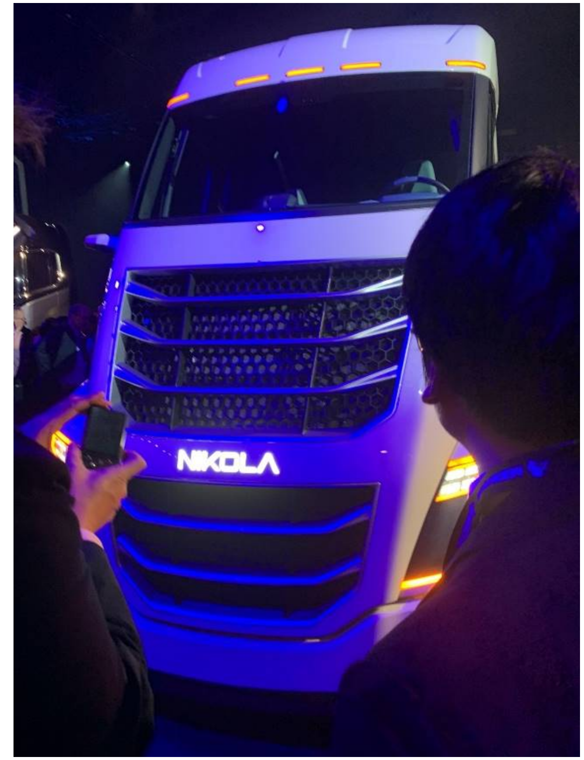
Fuel cell deployment will spread through products and market segments as it solves problems

Hydrogen End Use Applications

Drivers for Demand
Oil Refining
• Quality of crudes
• Air quality (removal of sulfur and aromatics)
• Demand for gasoline
Ammonia
• Demand for food crops
• Demand for biofuels
• Emerging applications, such as NOx control
• Demand for liquid carriers
Metal Refining
• Lower cost feedstock (recycled scrap)
• Cyclability
• Scalability
• Purity of resulting iron

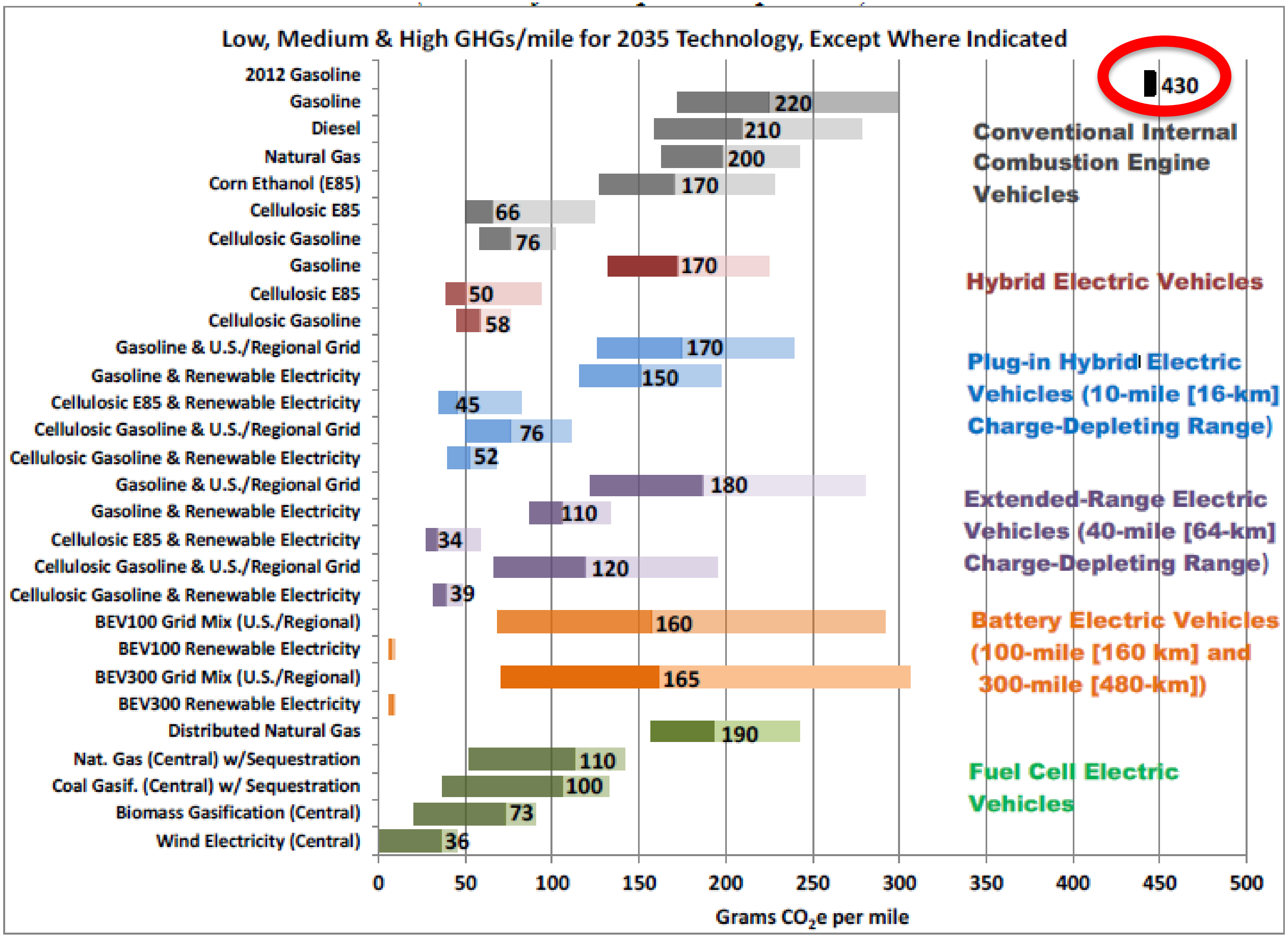
Technical and Market Needs
• Low-cost distributed H_2 production
• Co-electrolysis for methanol synthesis
• Identification of opportunities to use O_2 from electrolysis
• Valuation of renewable H_2 in regulatory frameworks
• Creation of "Sustainability Index" for investors
• Engineering of DRI reactors to manage kinetics in H2 (e.g. flash ironmaking technology)

Heavy-Duty, Buses



Toyota, Nikola, Ballard, UTC

Well-to-Wheels Greenhouse Gases Emissions for 2035 Mid-Size Car



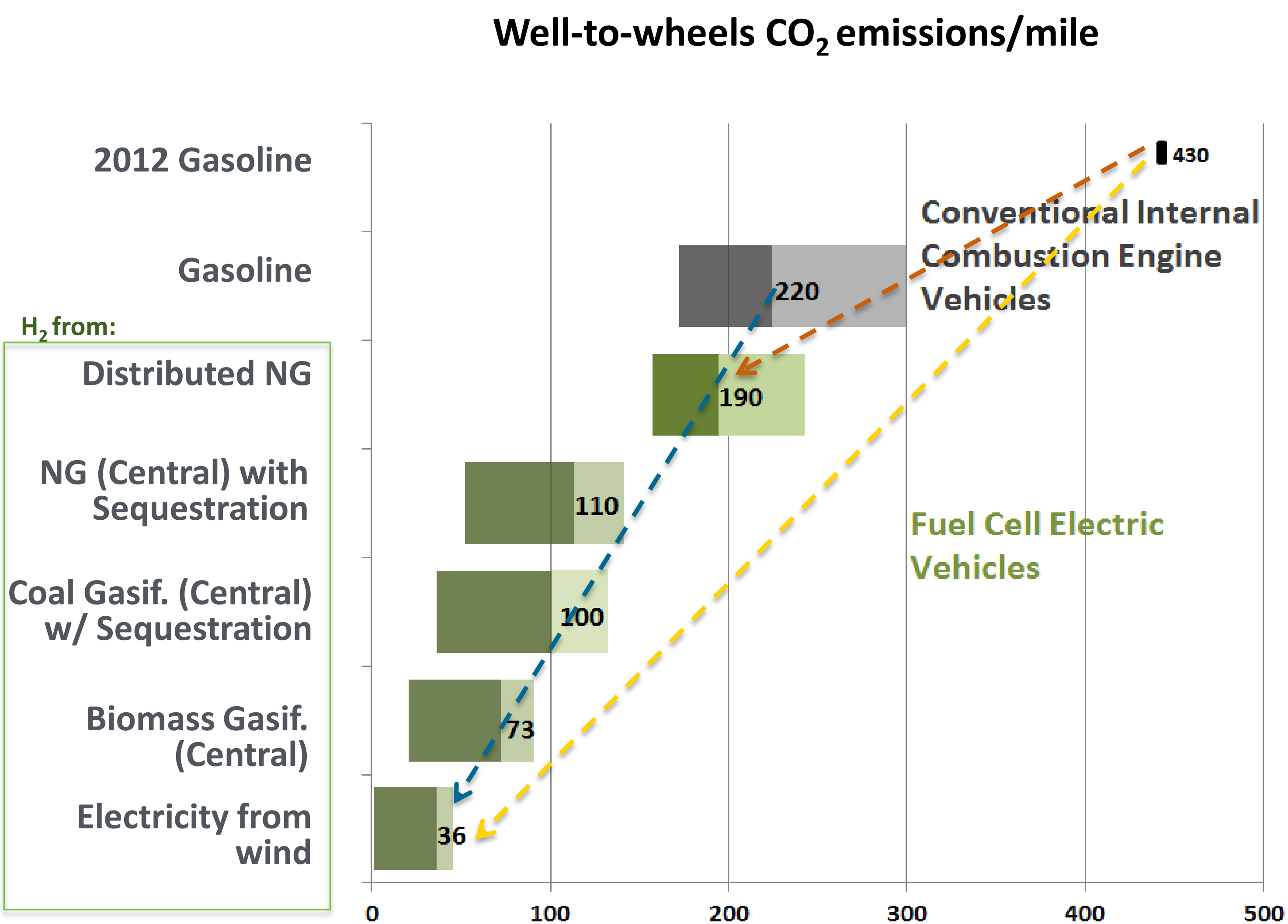
Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.

FCEVs Reduce Greenhouse Gas Emissions

>50% with H_2 from Distributed Natural Gas*

>80% with H_2 from Renewables* (Wind)

>90% with H_2 from Renewables** (Wind)



*Compared to 2035 gasoline vehicle
**Compared to 2012 gasoline vehicle

Source: http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf
Advanced 2035 technologies

Substantial GHG reductions with H_2 produced from renewables

Fuel Cells Show High Efficiency and a Large Range of Power Levels for Energy Conversion

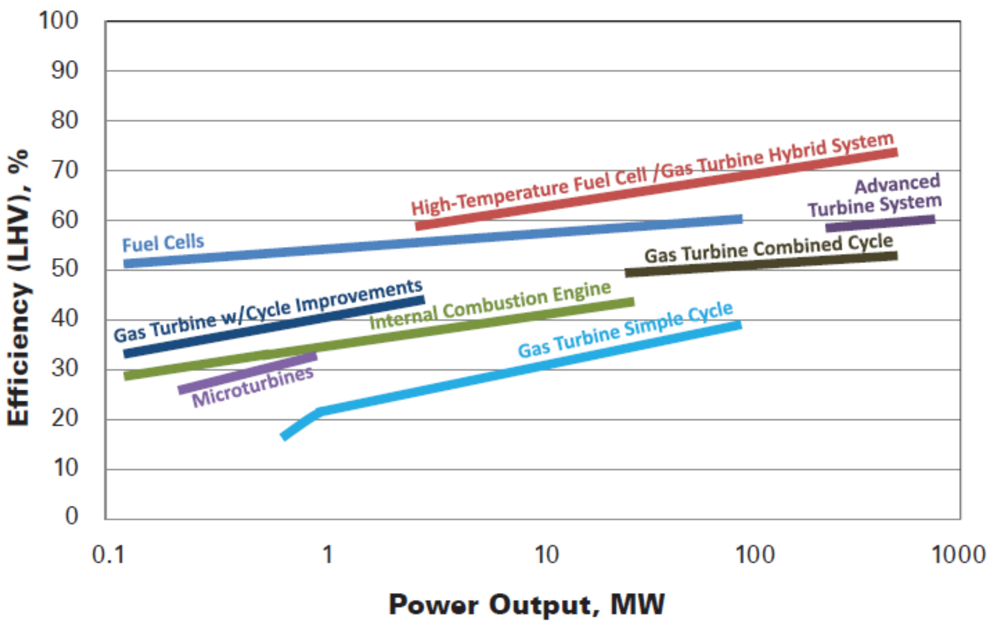


Figure 1.0. Power vs. Efficiency for Stationary Power Technologies. Fuel cells provide very high efficiency for stationary power generation, for a broad range of power output. The highest efficiencies are achieved by high-temperature fuel cell–turbine hybrid systems.[9]

Characteristic	Units	Status	2020 Target	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	$/kW$_e$	45 [e]	40	35

Conventional gasoline **vehicles** only convert about 17%–21% of the energy stored in gasoline to power at the wheels." An **electric motor** typically is between 85% and 90% **efficient**. ..

Toyota Mirai fuel cell car shows ~ 62% efficiency

Hydrogen Storage and Distribution

Examples of Research Needs

- **Delivery and Storage**
  - ✓ High-throughput compression for pipelines
  - ✓ Purification technologies to enable co-leveraging of infrastructure
  - ✓ Liquid carriers
- **Liquefaction**
  - ✓ Advanced expanders and compressors for mixed refrigerants
  - ✓ Non-mechanical approaches (e.g. magneto-caloric materials, thermo-acoustics)
  - ✓ Small-scale technologies
- **Cross-Cutting**
  - ✓ Capture of H_2 from existing process streams (e.g. chlor-alkali plants)
  - ✓ Development of skilled workforce

Current Status